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Ralph Stone and Co., Inc, Los Angeles, Calif

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Industrial Environmental Research Lab, Research Triangle Park, N C

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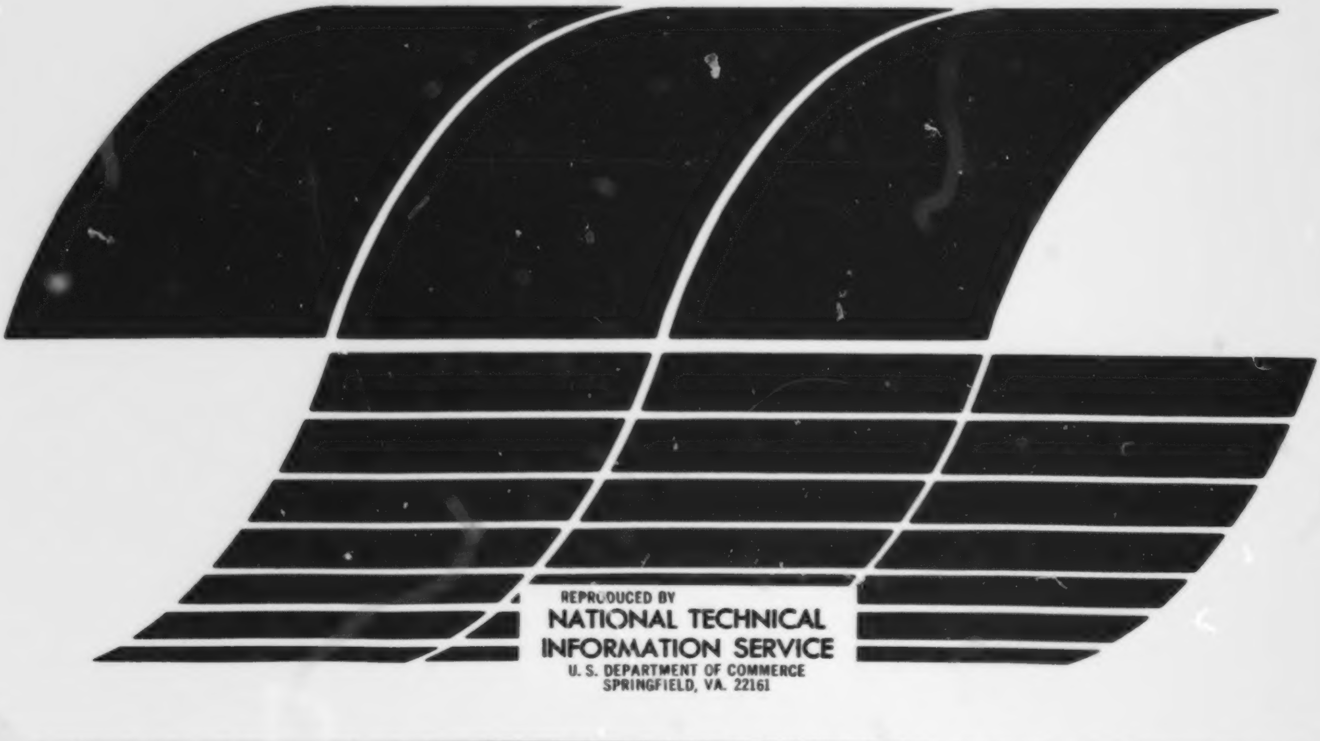
Interagency Energy/Environment R&D Program Report



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16. ABSTRACT

The report gives results of a 2-year study of the environmental assessment of solid residues generated by fluidized-bed combustion (FBC) of coal and gasification of oil. Included are a literature search, chemical and physical residue characterization, laboratory leaching studies, and testing of residues in various materials and agricultural applications. The literature search reviewed current FBC technology, identified products in which residues might be used, and gave data on typical soil and geologic conditions at the evaluated disposal sites. Laboratory tests included total chemical characterization, composition of acid-, base-, and water-soluble fractions, cation exchange capacity, BOD, temperature change from water addition, particle size distribution, dry density, specific gravity, permeability, water-holding capacity, moisture content, and small-scale column leaching studies. Pilot-scale columns simulated abandoned coal mines, dolomite and limestone quarries, sanitary landfills, soils, and the ocean. Water was added to columns on a prescribed schedule and the resulting leachate was collected and analyzed for chemical constituents. The data were used to assess the potential for impact on water quality, and the capacity of the disposal environment to attenuate degradation. Residue use was considered for concrete, asphalt, soil cement, and lime/flyash aggragate.

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Assessments	Fuel Oil	Stationary Sources	14B	
Solids	Gasification	Environmental Assessment	07D	
Residues	Water Quality			
Coal	Leaching	Fluidized-bed Combustion	21D	
Fluidized-bed Processing	Soils			08G,08M
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Environmental Assessment of Solid Residues from Fluidized-bed Fuel Processing: Final Report

by

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EPA Project Officer: Walter B. Steen

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Prepared for

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Office of Research and Development
Washington, DC 20460

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ABSTRACT

This report presents the results for an environmental assessment of the solid residues generated by fluidized-bed coal combustion and oil gasification. Tasks included a literature search, chemical and physical residue characterization, laboratory leaching studies, and testing of residues in various materials and agricultural applications.

The literature search reviewed current fluidized-bed combustion technology, identified products in which residues might be used, and provided data on typical soil and geologic conditions at the disposal sites being evaluated. Laboratory tests included total chemical characterization, composition of acid-, base-, and water-soluble fractions, cation exchanged capacity, BOD, temperature change from water addition, particle size distribution, dry density, specific gravity, permeability, water-holding capacity, moisture content, and small-scale column leaching studies.

Pilot-scale columns simulated limestone and dolomite quarries, sanitary landfills, abandoned coal mines, the ocean, and soils. Water was added to each column on a prescribed schedule and the resulting leachate was collected and analyzed for chemical constituents. The data were used to assess the potential for impact on water quality, and the capacity of the disposal environment to attenuate degradation.

Product tests and preliminary market analyses were conducted for residue use in concrete, asphalt, soil cement, and lime/fly ash aggregate. Uses as acid mine drainage neutralizer and agricultural soil conditioner/fertilizer were also evaluated.

This final report was submitted in fulfillment of Contract No. 68-03-2347 by Ralph Stone and Company, Inc., under the sponsorship of the United States Environmental Protection Agency. This report covers the period from November 5, 1975 to December 31, 1977.

CONTENTS

Page

Abstract ii
Figures v
Tables ix
Acknowledgments xv

1. Introduction 1

2. Summary 7
    Introduction 7
    Technical Approach 7

3. Conclusions 9

4. Recommendations 14

5. Fluidized-Bed Coal Combustion 15
    Introduction 15
    Process Descriptions 15

6. Residue Characterization 20
    Purpose 20
    Residue Characteristics 20
    Experimental Procedures 24
    Results 28

7. Pilot Column Studies of Residue Disposal 58
    Purpose 58
    Simulated Sedimentary Environment Columns 58
    Pilot Test Column Construction 74
    Leachate Sampling and Analyses 88
    Columns Operation During Sampling 97
    Results and Statistical Evaluation 98

8. Comparison of the Residue Characterization and Leaching Methods 159

CONTENTS (Cont.)

Page

9. Reuse Potential for Fluidized-Bed Residues 167
- Introduction 167
- Overall Reuse Prospects 167
- Types of Coal Ash 168
- Coal Ash Utilization 171
- Specific Applications for Coal Ash 178
- Specific Applications of Lime/Limestone Wet Scrubber Residues 200
- Potential Structural Materials Applications: Test Results 205
- Potential Agricultural Application of FBC Residues 216
- Marketing Analysis Methodology 248
- Economic Analysis of Specific Applications 251

References 257

Appendices 274

A. Laboratory Analytical Methods 274
B. Sample Data Sheet 278
C. Characterization of Similar Residues 281
D. Description of FBC Units - Providing Residues 291
E. Fluidized-Bed Oil Gasification 304

Glossary and Abbreviations 321

FIGURES

Number		Page
1	Direct contact fluidized-bed stream generator	16
2	Once through pressurized fluidized-bed boiler power plant	18
3	Laboratory-scale column leaching	25
4	BOD from residue water extracts	35
5	Leaching characteristics of NJFA and NJSBM	37
6	Leaching characteristics of VFA and VSBM	38
7	Leaching characteristics of EFA and ESBM	39
8	Temperature change from water addition to dry residues	49
9	Temperature change from water addition to dry residues	50
10	Particle size analyses: coal combustion residues	51
11	Particle size analyses: oil gasification residues	52
12	Particle size analyses: pea gravel, granite bedrock, and large gravel	53
13	Particle size analyses: silica sand and decomposed granite	54
14	Particle size analysis: coal, dolomite, and limestone	55
15	Legend for test column disposal environments	61
16	Abandoned limestone quarry test columns	63
17	Simulated sedimentary environment: dolomite quarry	64
18	Sanitary landfill test column	69
19	Stratigraphic section of a typical coal mine	71
20	Abandoned coal mine test column	73
21	Simulated sedimentary environment: sea water	75
22	Original location of representative soil samples	77
23	Simulated sedimentary environment: sandy, clayey and silt soils test column	78

FIGURES (cont.)

Number		Page
24	Lysimeter construction and test column placement	85
25	Outdoor columns leachate sampling apparatus	87
26	Drainage through limestone quarry columns	88
27	Drainage through dolomite quarry columns	90
28	Drainage through sanitary landfill columns	91
29	Drainage through coal mine columns	96
30	Drainage through ocean disposal columns	93
31	Typical test column leachate collection system schematic	27
32-37	Constituents leachated from test columns: NJFA	117
38-43	Constituents leached from test columns: NJSBM	118
44-49	Constituents leached from test columns: VFA	120
50-55	Constituents leached from test columns: VSBM	121
56-61	Constituents leached from test columns: EFA	123
62-67	Constituents leached from test columns: ESBM	124
68	Effect of freeze-thaw cycles on LCFA compressive strength	182
69	Change of length with temperature for cured LFA specimen	183
70	Effect of curing time and temperature on LFA compressive strength	184
71	Effect of curing time and temperature on LCFA compressive strength	185
72	Effect of lime content and curing conditions on LFA strength	188
73	Effect of fly ash on LFA density	189
74	LFA moisture correlation chart	192
75	pH leachate for acid mine drainage	194
76	Aerated or foamed cellular concrete production flow diagram	202
77	Formed concrete production flow sheet	203
78	CS brick production flow diagram	204
79	Concrete compressive strength tests: NJFA, VFA, VSBM after seven day cure	212
80	Concrete compressive strength tests: NJFA, VFA, VSBM after 28-day cure	213

FIGURES (Cont.)

Number		Page
81	Concrete compressive strength tests: NJSBM, ESBM, EFA after 7-day cure	214
82	Concrete compressive strength tests: NJSBM, EFA, ESBM after 28-day cure	215
83	Result of reaction between residues and emulsified asphalt	218
84	Asphalt compressive strength tests: VSBM, NJSBM, ESBM after 29-hour cure	219
85	Asphalt compressive strength tests: VSBM, NJSBM, ESBM after 7-day cure	220
86	Asphalt compressive strength tests: NJFA, EFA after 29-hour cure	221
87	Asphalt compressive strength tests: NJFA, EFA after 7-day cure	222
88	Experiment 2-A tomato plant growth	226
89	Mean tomato plant height, experiment 2: VFA, FSFA, CFA	229
90	Mean tomato plant height, experiment 2: NJSBM, VSBM, NJFA	230
91	Tomato plant growth vs soil pH, experiment 2-A	233
92-95	Experiment 2A: analytical results of calcium, magnesium, sulfate, and manganese	236
96-99	Experiment 2B: analytical results of calcium, magnesium, cadmium, and copper	238
100-103	Experiment 2B: analytical results of iron, manganese, zinc, and silver	239
104-107	Experiment 3: analytical results of calcium, magnesium, cadmium, and copper	243
108-111	Experiments 3 and 4: analytical results of iron, lead, calcium, and magnesium	244
112	Distance to U.S. coal-fired power plants	249
C-1	Concentration range and average of U.S. fly ash constituents	285
D-1	FBC construction detail (side view)	292
D-2	FBC construction detail (front view)	293
D-3	Fluidized bed module: internal construction	295

FIGURES (Cont.)

Number		Page
D-4	FBM and regenerator flow diagram	296
D-5	Section view of the integrated BVM/CBC unit	298
D-6	Bed material flow paths FBM, CBC regenerator	299
D-7	Pressurized FBC pilot plant, Linden, New Jersey	300
D-8	Exxon FBC unit	303
E-1	Low pressure fluidized bed oil gasification for power generation	305
E-2	High pressure fluidized bed oil gasification for power generation	306
E-3	Modes of operation, fluidized bed oil gasification plant	307
E-4	Energy balances flow diagram	311
E-5	Regenerative high-pressure oil gasification process	312
E-6	Esso, England oil gasification system	319
E-7	Batch reactor	320

TABLES

Number		Page
1	U.S. Electric Generating Capacity	2
2	U.S. Electricity Generation by Type of Fuel: 1970-1990	2
3	Projected Annual Fuel Requirements: Steam Electric Power Plants	3
4	Potential U.S. Sulfur Dioxide Pollution with No Abatement	3
5	Sulfur Dioxide Abatement Processes	4
6	Identification of Residues	6
7	Comparison of FBC Sorbent Processes	19
8	Pilot Plant Operation for Characterized Residues	21
9	Characterization of Pope, Evans, and Robbins Bituminous Coal Samples	22
10	Characterization of Pope, Evans, and Robbins Calcined Limestone Samples	23
11	Characterization of Exxon Miniplant Coal Samples	23
12	Stratigraphic Materials Simulated in Leaching Tests	26
13	Total Digestion Characteristics of Fluidized-Bed Residues	29
14	Soluble Salt Extraction Characterization of Residues I. Exxon Miniplant, Linden, New Jersey	31
15	Soluble Salt Extraction Characterization of Residues II. Pope, Evans, and Robbins, Alexandria, Virginia	32
16	Soluble Salt Extraction Characterization of Residues III. Esso, Great Britain	33
17	Soluble Salt Extraction Characterization of Residues IV. Esso, Great Britain	34
18	Laboratory Leaching Tests: Limestone	40
19	Laboratory Leaching Tests: Dolomite	41
20	Laboratory Leaching Tests: Bituminous Coal	42
21	Laboratory Leaching Tests: Claystone	43

TABLES (Cont.)

Number		Page
22	Laboratory Leaching Tests: #60 Silica Sand	44
23	Laboratory Leaching Tests: #16 Silica Sand	45
24	Laboratory Leaching Tests: Granite Bedrock	46
25	Residue Acid Neutralization Capacity	47
26	Residue Cation Exchange Capacity	47
27	Residue Physical Properties	56
28	Permeability of Residues and Column Materials	57
29	Column and Residue Identification	59
30	Representative Thickness of Limestone and Dolomite Simulation Test Columns	62
31	Estimated Residential and Commercial Solid Waste Generation by Kind of Material and Product Source Category, 1971	65
32	Sanitary Landfill – As Mixed Test Column	68
33	Representative Thickness Sanitary Landfill Simulated in Test Columns	70
34	Representative Thickness of Coal Mine Simulation Test Column	72
35	Test Column Soils Characteristics	76
36	Criteria Definition for Grading Analysis	80
37	Column Materials Grading Analysis	81
38	Material Densities of Natural Strata and Test Columns	82
39	Materials in Test Column Layers by Weight	83
40	Residues Added to Columns	86
41	Complete Analysis of Los Angeles Owens River Aqueduct (Potable (Water) Columns Test	94 94
42	Constituents Present in Sea Water	95
43	Analyses of Sea Water Applied to the Test Columns	96
44	Summary of Fluidized Bed Combustion Column Contents	99
45	Variation in Limestone Quarry Column Leachate Constituents	102
46	Variation in Dolomite Quarry Column Leachate Constituents	103
47	Variation in Sanitary Landfill Column Leachate Constituents	104
48	Variation in Coal Mine Column Leachate Constituents	105

TABLES (Cont.)

Number Page

49 Variation in Ocean Column Leachate Constituents 106

50 Variation in Sandy, Clayey, and Silty Soils Column Leachate Constituents 107

51 Constituents Removed by the Test Columns: NJFA 109

52 Constituents Removed by the Test Columns: NJSBM 110

53 Constituents Removed by the Test Columns: VFA 111

54 Constituents Removed by the Test Columns: VSBM 112

55 Constituents Removed by the Test Columns: EFA 113

56 Constituents Removed by the Test Columns: ESBM 115

57 EPA Interim Primary Drinking Water Regulations, 1975 and Water Quality Criteria for Beneficial Uses 127

58 Recommended Maximum Concentrations of Trace Elements in Irrigation Waters 131

59 Comparison of Limestone Column Leachate Constituents with Water Quality Criteria for Municipal Water Supplies 132

60 Comparison of Dolomite Column Leachate Constituents with Water Quality Criteria for Municipal Water Supplies 133

61 Comparison of Sanitary Landfill Column Leachate Constituents with Water Quality Criteria for Municipal Water Supplies 134

62 Comparison of Coal Column Leachate Constituents with Water Quality Criteria for Municipal Water Supplies 135

63 Comparison of Sandy, Clayey, and Silty Soils Column Leachate Constituents with Water Quality Criteria for Municipal Water Supplies 136

64 Leachate Analyses of the Test Columns from the NJFA 138

65 Leachate Analyses of the Test Columns from the NJSBM 140

66 Leachate Analyses of the Test Columns from the VFA 142

67 Leachate Analyses of the Test Columns from the VSBM 144

68 Leachate Analyses of the Test Columns from the EFA 146

69 Leachate Analyses of the Test Columns from the ESBM 150

70 Leachate Analyses of the Test Columns 154

TABLES (Cont.)

Number		Page
71	Comparison of Four Methods for Determining the Leaching Characteristics of NJFA	160
72	Comparison of Four Methods for Determining the Leaching Characteristics of NJSBM	161
73	Comparison of Four Methods for Determining the Leaching Characteristics of VFA	162
74	Comparison of Four Methods for Determining the Leaching Characteristics of VSBM	163
75	Comparison of Four Methods for Determining the Leaching Characteristics of EFA	164
76	Comparison of Four Methods for Determining the Leaching Characteristics of ESBM	165
77	Estimated Ash Utilization Potential	169
78	Comparison of Ash Compositions	170
79	Comparison of FBC Residue Compositions	170
80	Comparative Ash Production and Utilization, 1966 through 1972	172
81	Ash Collection and Utilization, 1971	173
82	Known Miscellaneous Uses for Ash and Slag	174
83	Known Uses for Ash Removed from Plant at No Cost to Utility, 1971	176
84	Density of Fly Ash Compared with Traditional Fills	177
85	Development of Ash Production and Use in the Economic Commission for Europe Region	179
86	Effect of Fly Ash Content on LFA Strength and Durability	186
87	Average Cement Requirements of Miscellaneous Materials	196
88	Normal Range of Cement Requirements for B and C Horizon Soil	196
89	Effect of Adding Zn and Varying the pH in the Soil on Zn Content and Yield Reduction of Chard Leaves	198
90	Effects of Soil pH on Soybean Plants' Mineral Uptake	199
91	Potential Structural Materials Applications: Tests Performed	206
92	Composition of Concrete Test Cylinders	207
93	Diameter and Area of Concrete Test Cylinders: Seven-Day Cure	208

TABLES (Cont.)

Number		Page
94	Diameter and Area of Concrete Test Cylinders: Twenty-eight Day Cure	209
95	Results of Compressive Concrete Strength Test After Seven Days	210
96	Results of Compressive Concrete Strength Test After Twenty-Eight Days	211
97	Asphalt Sample Compositions	217
98	Planting Schedule for Agricultural Tests	224
99	Experiment 2-A: Tomato Plant Growth Results	227
100	pH of Soil Residue Mixture	231
101	pH of Soil Residue Mixture After Crop 2 Harvest	232
102	Experiment 2-A: Tomato Plant Tissue, Chemical Analyses	235
103	Experiment 2-B: Tomato Plant Tissue, Chemical Analyses	237
104	Experiment 3: Spinach Tissue, Chemical Analyses	241
105	Experiment 4: Lettuce Tissues, Chemical Analyses	246
106	Sludge Fixation Costing Estimates	252
107	Residue Value for Use in Concrete	253
108	Imputed Value of Residues in Asphalt Applications	254
109	Fluidized-Bed Residues as a Substitute for Calcium Carbonate in Peanut Growing	256
A-1	Soil Preparatory Methods	275
A-2	Soil Tests	275
A-3	Analytical Methods	276
C-1	Common Minerals in U.S. Coals	282
C-2	Chemical Constituents in Coal Ash	282
C-3	Coal Ash Solubility in Distilled Water	283
C-4	Mineral Phases Found in Coal Ash	283
C-5	Physical Properties of Fly Ash from Pulverized Coal Fired Plants	284
C-6	Oxide Analyses of Incinerator Fly Ash from Typical Refuse	286
C-7	Elemental Head Sample Analyses of Municipal Incinerator Fly Ashes	287
C-8	Wet Chemical Analysis of Sludge Standards	288

TABLES (Cont.)

Number		Page
C-9	Identification of APCS Sludge Standards	289
C-10	X-ray Analysis of APCS Sludges	290
D-1	Design Parameters: Exxon Miniplant	301
E-1	Atmospheric Pressure Oil Gasification Specifications	308
E-2	Specifications for Fluidized Bed Operation	310
E-3	Gasification Product Compositions	314
E-4	Environmental Impact Comparison	315
E-5	Advantages of Atmospheric Pressure Oil Gasification Over Stack Gas Wet Scrubbers	316
E-6	Summary of Experimental Results	318

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CHAPTER 1

INTRODUCTION

Total electricity consumption in the United States was projected to increase at an annual rate of 7 to 8 percent over 1970-1990. The relative shares of coal, oil, gas, and hydroelectric generation were expected to decrease as nuclear sources come to predominate. These trends are shown in Tables 1 and 2. However, the absolute quantities of coal and oil used should increase along with total consumption. Projected fuel usage requirements are shown in Table 3.

Combustion of more coal and oil implies increased sulfur oxides generation, as shown in Table 4. This may be aggravated by a projected increase in the average sulfur content of coal burned, from the current 2.7 percent to 3.5 percent by the 2000. Airborne sulfur compounds are associated with damage to human health, vegetation, and materials. There are many ways being researched to reduce sulfur oxide emissions, as shown in Table 5.

One approach to alleviating the problem is to develop ways of burning high sulfur fuels without high-sulfur oxide emissions. Among the options being researched are fluidized-bed combustion of high sulfur coal and fluidized-bed gasification of high sulfur residual oils. The Environmental Protection Agency has been evaluating two high sulfur coal fluidized-bed combustion pilot plants. The United States Energy Research and Development Administration (ERDA) has been supporting one small scale and one large scale pilot plant. One high sulfur residual oil fluidized-bed reactor pilot plant has been operating in England under an Environmental Protection Agency international agreement. In these plants, either pulverized limestone or dolomite bed material was admixed to the coal or oil being burned. The sulfur in the fuels reacted with the bed material to form calcium and magnesium sulfates and, to some degree, sulfites and sulfides. Gaseous sulfur emissions were thus greatly reduced, but solid residues were increased. These residues consisted of calcium and magnesium oxides (from unreacted portions of dolomite and limestone), calcium and magnesium sulfur compounds, traces of unburned coal and oil and their stack and bottom ash, and inert matter originating from natural dolomite or limestone.

The disposal of these residues has been a matter of concern since toxic substances might be leached from the residues into ground or surface waters. This study was initiated because there had been no extensive research into the environmental impacts of the disposal of these solid residues or the feasibility of their recovery.

The general objective of this project was to assess the environmental impact of the disposal or the recovery of the residues which would be generated with widespread commercial use of the fluidized-bed process for high sulfur coal combustion and gasification of high sulfur residual oil. Specific objectives were to:

- Determine the chemical and physical characteristics of the residues from the fluidized bed process applied to coal and oil.

TABLE 1. U. S. ELECTRIC GENERATING CAPACITY

Type of Plant	1970(Actual) Capacity (10^{3}Mw)	% of Total	1980 (Projected) Capacity (10^{3}Mw)	% of Total	1990 (Projected) Capacity (10^{3}Mw)	% of Total
Fossil steam	260	76	393	59	557	44
Nuclear steam	6	2	147	22	500	40
Steam subtotal	266	78	540	81	1,057	84
Hydroelectric – conventional	52	15	68	10	82	6
Hydroelectric – pumped storage	4	1	27	4	71	6
Gas turbine and diesel	19	6	31	5	51	4
Totals	341	100	666	100	1,261	100

Source: 159.

TABLE 2. U. S. ELECTRICITY GENERATION BY TYPE OF FUEL: 1970–1990

	Percent of Total Generation				
Year	Coal	Oil	Gas	Nuclear	Hydroelectric
1970	46.4	11.8	24.2	1.4	16.2
1980	36.5	12.4	12.4	27.6	11.1
1990	26.7	8.0	7.2	47.3	10.8

Source: 159.

TABLE 3. PROJECTED ANNUAL FUEL REQUIREMENTS: STEAM ELECTRIC POWER PLANTS

Fuel	Unit	1970	1980	1990
Coal	10^6 kkg	292	454	635
Natural gas	10^9 cu m	185	106	118
Residual fuel oil	10^6 bbl	331	640	800
Uranium ore	kkg[a]	6,800	37,000	115,000

[a] kkg of U_3O_8 required to supply feed for diffusion plants without plutonium recycle.

Source: 158.

TABLE 4. POTENTIAL U. S. SULFUR DIOXIDE POLLUTION WITH NO ABATEMENT

Source	Annual Emission of SO_2 (kkg)				
	1967	1970	1980	1990	2000
Power plant operation (coal and oil)	13.6	18.1	37.3	56.2	85.7
Other combustion of coal	4.6	4.4	3.6	2.8	1.5
Combustion of petroleum products (excluding power plant oil)	2.5	3.1	3.5	3.9	4.6
Smelting of metallic ores	3.4	3.6	4.8	6.4	8.7
Petroleum refinery operation	1.9	2.2	3.6	5.9	9.5
Miscellaneous sources[a]	1.8	1.8	2.4	3.1	4.1
Total	27.9	22.2	55.2	78.4	114.1

[a] Includes coke processing, H_2SO_4 plants, coal refuse banks, refuse incineration, and pulp and paper manufacturing.

Source: 160.

TABLE 5. SULFUR DIOXIDE ABATEMENT PROCESSES

1. Precombustion processes
    - a. Coal and oil cleaning
    - b. Coal and oil gasification
    - c. Fluidized bed gasification
2. Combustion processes
    - a. Fluidized bed combustion
    - b. Black, Sivalls, and Bryson
3. Limestone processes
    - a. Wet scrubbing
    - b. Dry removal
4. Processes for sulfur recovery from stack gases
    - a. Cat - O_x
    - b. Wellman-Lord
    - c. Esso-Babcock & Wilcox adsorbent
    - d. Formate scrubbing
    - e. Ammonia scrubbing
    - f. Westvaco char
    - g. Molten carbonate
    - h. Sodium bicarbonate adsorption
    - i. Modified Claus
    - k. Catalytic chamber
    - l. Ionics/Stone & Webster
    - m. Alkalized alumina

- Identify the leachate water pollution constituents and quantities resulting from land and ocean disposal of residues.

- Evaluate the potential effects of disposing the residues into different soil and sedimentary environments and into the ocean.

- Investigate the potential for recovery of the solid residues.

- Determine the needs for treating the residues and establishing methods for the disposal of such wastes.

Literature reviews, and the results from residue characterization and pilot test columns evaluation were used to determine the potential environmental impacts of disposing solid residues from fluidized-bed operations. Residues from both the fluidized-bed combustion of high sulfur coal and fluidized bed gasification of high sulfur residual oils were tested. Residues,obtained from three pilot plants, are identified in Table 6; the symbol abbreviations shown will be used throughout the report in reference to the three pilot plants. The glossary describes unique report terminology and abbreviations.

In general, the literature search provided information on the disposal and environmental impacts of similar residues such as coal ash or limestone SO_x scrubber wastes. Information on similar types of waste residues were obtained in laboratory and pilot test reports. From available sources, estimates were made of the conditions for and the levels of pollutants anticipated from the residue wastes in various environments. Process descriptions of material flows for plants generating FBC and CAFB residues were obtained. Typical natural conditions were selected for our study work. The results of the literature search were of value in designing the specific limits and developing a detailed monitoring program for the laboratory and column tests.

The laboratory studies, including residue characterization, were used to constuct pilot-scale test columns which simulated land and ocean disposal environments on a small scale. The land disposal simulated environments which were evaluated were limestone and dolomite quarries, sanitary landfill, abandoned coal mine, ocean, and sandy, clayey, and silty soils. All leachate was collected and analyzed, and profiles of the leachate results for the various disposal methods were determined.

Studies were also undertaken to determine the possibility of recovering and marketing the residues instead of disposing of them. Laboratory tests were conducted to determine the feasibility of using these residues for commercial products. These tests compared the properties of materials produced using residues with those made with conventional raw materials. A preliminary market study was initiated to determine the market potentials for the residues and their finished products. Concurrent with the product feasibility task, an evaluation of requirements for treating residues was initiated to establish whether treatment can enhance product use or is required for disposal.

TABLE 6. IDENTIFICATION OF RESIDUES

Symbol	Residue Source	Descriptive Name of Residue	Pilot Plant Location
CFA[a]	Oil	Cyclone fly ash	Esso; Abingdon, England
FSFA[a]	Oil	Fines, stack, regenerator, gasifier, fly ash	Esso; Abingdon, England
VFA	Coal	Virginia fly ash	Pope, Evans, and Robbins; Alexandria, Virginia
VSBM	Coal	Virginia spent bed material	Pope, Evans, and Robbins; Alexandria, Virginia
NJFA	Coal	New Jersey fly ash	Exxon; Linden, New Jersey
NJSBM	Coal	New Jersey spent bed material	Exxon; Linden, New Jersey
EFA[b]	Oil	English fly ash	Esso; Abingdon, England
ESBM[b]	Oil	English spent bed material	Esso; Abingdon, England

[a] CFA and FSFA residue were not used in the latter part of this study because of insufficient quantities.

[b] EFA and ESBM were obtained to replace the CFA and FSFA residues.

CHAPTER 2

SUMMARY

Introduction

The overall purpose of the proposed work was to determine the environmental impact of the disposal of residues from the fluidized-bed combustion of high sulfur coal, and fluidized-bed gasification of high sulfur residual oil. The specific objectives were to determine:

1. The physical and chemical characteristics of the solid, sludge, and liquid residues from the fluidized-bed processes applied to coal and oil.

2. The leachate constituents and quantities from land and ocean site disposal of the residues.

3. Other potential environmental effects from disposing the residues into alternative land and water sites.

4. The potential for utilizing solid residues for manufacture of commercial products and for other purposes.

5. Pretreatment requirements for the residues, prior to their disposal.

Technical Approach

Literature reviews and laboratory tests, including residue characterization and pilot test columns evaluation, were done to determine the environmental impacts of disposal of solid residues from fluidized-bed operations. Residues from fluidized-bed combustion of high-sulfur coal and fluidized-bed gasification of high-sulfur residual oils were obtained from three pilot plants; two were supported by the Environmental Protection Agency, and one was supported by Energy Research and Development Administration. The three plants were: Pope, Evans, & Robbins-FBM Combustion Laboratory, Alexandria Virginia, burning Pennsylvania coal; Exxon Research & Engineering Company, Linden, New Jersey, burning Illinois fuel; and Esso Petroleum Company, Limited, Abingdon, Oxon, England, gasifying No. 6 Venezuelan oil.

The literature search provided information on the disposal, reuse, and environmental impacts of similar residues, such as coal ash or SO_x limestone scrubber wastes. Information on the types of waste residues from these processes summarized in laboratory and pilot test reports were also obtained. From these sources, estimates were made of the conditions for and the levels of pollutants anticipated from the wastes in various environments. Process descriptions of material flows for the three plants were obtained from the Environmental Protection Agency and The Energy Research and Development Administration authorities. Models of the subject disposal environments were developed from the literature and were used to predict the various natural site conditions, limits, and goals.

A comprehensive program of residue characterization was initiated to determine the chemical and physical properties of the six fluidized-bed residues. The resultant physical property data was used to hydraulically design 36 pilot test columns for leachate studies. The resultant chemical property data was used to determine the constituents to be monitored during the test columns study.

Pilot plant type studies were used to simulate, on a smaller scale, eight disposal environments: limestone and dolomite quarries, sanitary landfill, abandoned coal mine, ocean and sandy, clayey and silty soils. By evaluating pilot scale test columns, the environmental variables that would affect the behavior of the residues in natural environments were controlled. All leachate was collected and analyzed, and precise analytical profiles of the residues and their disposal conditions were established. Large-scale field test programs were postponed when it proved impossible to obtain sufficient quantities of residues. To compensate, the pilot scale test columns study and product testing were expanded.

Studies were undertaken to determine the possibility of recovering and marketing the residues instead of disposing of them. The results of bench tests were used to evaluate the residues' uses in the manufactuing of certain commercial products. These tests compared the properties of the recovered product with that produced using conventional raw materials. The use of residues in concrete, asphalt, soil cement, lime-fly ash-aggregate and lime-fly ash-cement, aggregate mixtures, and as load bearing fill were evaluated. Concurrent with the product feasibility task, an evaluation of requirements for treating residues was made to see if pretreatment can enhance product use or is required for disposal.

Potential use of the spent residues as soil conditioners for agricultural purposes was also investigated. A variety of crops (tomato, spinach, and lettuce) were grown in mixtures of fluidized-bed residue and soil. The use of the residues as a soil conditioner and neutralizer of acidic soil was evaluated. Acidic soils may contain high levels of boron and manganese which are easily soluble and sometimes believed to be toxic to crops; however, it has been known for a long time that an increase in pH will decrease the uptake of heavy metals. Lime has been used to help increase the pH but the residues could presumably replace the lime, and thus decrease these toxic metals. Conversely, residues provide an excellent source of trace metals and nutrients needed by plants.

CHAPTER 3

CONCLUSIONS

Fly ash and spent-bed residues from coal combustion and oil gasification in fluidized beds were characterized for their physical and chemical properties, evaluated for their impact on simulated land and ocean environments, and assessed for reuse potential. The residues were obtained from cooperating pilot plants operated by representatives of Exxon, Linden, New Jersey; Pope, Evans, and Robbins, Alexandria, Virginia; and Esso, Great Britain. The specific residues studied are listed in Table 6. The following conclusions are based upon the investigations described in the body of the report.

Literature Review

1. A comprehensive review of literature indicated that no historical environmental data existed on coal fluidized-bed combustion and oil gasification, other than progress reports on the various pilot plants and technologies currently under development.

2. There was no reported experience with operating a full-scale commercial fluidized-bed power plant prior to or during this investigation.

3. The literature review and data developed from over 200 different sources during the duration of this project report indicated the following differences between fly ash from fluidized-bed combustion and conventional coal and oil-fired combustion:

- Residues from fluidized-bed combustion (FBC) are derived from spent limestone and fly ash, while conventional coal combustion residues come from dolomite or lime scrubber sludges and fly/bottom ashes.

- Fluidized-bed combustion normally produces solid residues, whereas conventional combustors with scrubbers produce liquid sludges as well as some bottom ash solids.

- Test fluidized-bed fly and bottom ash samples were dry, whereas conventional combustion plant ashes were wetted to quench burning coals and to cool the residues.

- The FBC residue samples had higher specific gravities (generally 2.6 to 2.8) than conventional fly ash, and thus would not be as suitable for use in lightweight concrete and structural fills.

- The FBC fly/bed test residues were recirculated and hence contained less organic material compared to conventional unrecirculated residues.

Residue Characterization

1. The measurement of the moisture content indicated that the fluidized-bed residues, when received, contained no significant moisture.

2. All residues except NJFA reacted exothermically, reaching temperatures up to 220°C within 16 minutes after addition of water. These reactions were attributed to lime slaking.

3. The fluidized-bed material particle sizes as received were in the range of fine, sandy soil, (0.1 to 1.0mm diameter) and the specific gravities (2.6 to 2.8 for all the residues except EFA which was 2.02) were similar to normal soils.

4. BOD (biochemical oxygen demand) test results indicated that residue leachates contained constituents which acted as temporary inhibitors of microorganism growth.

5. The leachates from the fluidized-bed residues were highly basic(generally greater than a pH of 11); thus, the residues may be used to neutralize acidic soils and other acidic material.

6. The solubility characteristics of the fluidized-bed residues were influenced by changes in the pH of the solution added to the residues. Using, soluble salt extraction tests (shake tests), it was determined that an acidic pH generally increased the leaching of heavy metals and increased the concentration of calcium by 2,000 to 4,000 percent. The solubility of sulfate was much greater in the base soluble extracts than in the acid and water soluble fractions.

7. Bench scale leaching tests indicated that chlorides from VFA, VSBM, and ESBM, and zinc from NJFA were readily leached; whereas chlorides from NJFA, NJSBM, and EFA were leached at a slower and a relatively constant rate. Sulfates, iron, nickel, lead, and zinc (other than NJFA) were also leached at a slower, yet constant rate.

Pilot Column Studies of Residual Disposal

Eight simulated residue disposal environments were evaluated in 20.3 cm diameter by 3 m high test columns. The environments included limestone and dolomite quarries, sanitary landfill, coal mine, ocean environment, and sandy, clayey, and silty soils.

1. The sanitary landfill and the sandy, clayey, and silty soils were shown to be the most effective simulated environments for disposing of fluidized-bed residues. The other four simulated environments reduced the concentrations of trace metals and other constituents in the residue leachate, but not to the extent of the former environments.

2. Some of the residues, particularly NJFA and VSBM, solidified and became impervious to water several months after placement in the columns. The solidification of the residues was caused by consolidation and hydrolization.

3. Of the four most effective simulated environments, the sanitary landfill may be considered the best environment for disposing of fluidized-bed residues. The sanitary landfill test columns were, by far, the most effective in removing sulfate (some 90 percent compared to 25 to 75 percent removal from the other environments). Disposal of the highly alkaline fluidized-bed residues would be most beneficial in neutralizing the acidic content of the sanitary landfill.

4. The residues from Esso, Great Britain, contained higher quantities of constituents, and their disposal in general showed higher contamination of the water passing through the test columns.

5. The simulated disposal of VFA onto any of the test environments resulted in less water pollution impact than the other residues, i.e., the leachate constituents exceeded the interim primary drinking water quality criteria only 20 percent of the time (16 percent when leached through the sanitary landfill simulated environment), while the other residues exceeded the permissible drinking water criteria more than 28 percent of the time.

6. The EPA primary drinking water contamination level for zinc (5.0 mg/l) in the test column leachates was not exceeded, and the recommended chloride level (250 mg/l) was exceeded only by the leachate coming from the EFA and ESBM residues for all environments.

7. During the last eight months of the pilot test columns' study, the water quality criteria for copper (1.0 mg/l), mercury (0.005 mg/l), and nitrate (10 mg/l), were not exceeded for any simulated environment, and the recommended irrigation water contaminant level for aluminum (5.0 mg/l) was not exceeded. Only NJFA and NJSBM leachates from the dolomite test column and the NJSBM leachate from the coal mine test column exceeded the cadmium (0.01 mg/l) water quality criteria.

Comparison of Difference Leaching Methods.

This study provided four basically different methods for evaluating the leaching characteristics of residue materials. The four accelerated test methods, as described in Chapter 8, were total residue digestion, soluble salt extraction test, residue leaching test, and pilot column leaching test. The results show that there were no consistent relationships in the data among the four methods; however, the following conclusions can be made. (1) The "total residue acid digestion" did not replicate the leaching characteristics of residues in the natural water environment. The digestion broke down the residue into a totally soluble form which generated some higher constituent concentrations which were not obtained in the water leaching. (2) The results of the "soluble salt extraction" analyses (i.e., the shake test) showed that incomplete leaching occurred. These extracts showed that highly soluble chlorides as well as other constituents were lower in concentration than those which were obtained by the "pilot column" leaching tests. Thus, the "soluble salt extraction" (shake test) was not accurate in interpreting the potential leaching of residues in the environment tested. (3) The bench scale "residue leaching test" generally gave values higher than those found in the larger pilot-scale column leaching tests. This is understandable because in the larger columns, the stratum simulation of the environment attenuated some of the dissolved constituents. No two methods gave similar results; however, since the residues percolated through known subsurface materials, the analytical results from the pilot test columns tests appeared to most effectively simulate the potential leaching impacts of residues on the natural environment.

Reuse Potential for Fluidized-Bed Residues.

The FBC fly ash and bed materails have potential for many beneficial reuses, such as additives for concrete, road bed stabilization, fill material, soil stabilization, soil cement, and brick manufacture. They also have potential use in neutralization of acid mine drainage, rectification of acidic or other deficient soils in agricultural pursuits, water treatment, roadway de-icing, and so forth. Fluidized-bed residues have a potential for many uses presently provided by clay, lime, or dolomite.

1. The potential market for fluidized-bed residues requires development. Only a small amount (only about 17 percent of the conventional coal ash) has been reused since 1968. However, the potential market for fluidized-bed residues may be greater because of the valuable high calcium and magnesium content present. Although use of high-ash fuels has increased as low-ash fuels have been depleting, the changeover to reusing fluidized-bed residues may be slow because potential users will stay with the available large quantities of conventional coal or oil ashes, and will resist adopting a new residue until its value has been proven. The physical and chemical characteristics of the fluidized-bed residues were found to be substantially different from that of conventional coal or oil ash residues.

2. The compressive strength of concrete generally increased with the addition of five percent VSBM, NJFA, and VFA. The other fluidized-bed materials did not improve the compressive strength of the concrete.

3. Fluidized-bed residues may be added to portland cement as a partial replacement for some aggregate and to reduce the amount of costly cement. The substitution would save about $0.50 per kkg of equivalent strength concrete.

4. The use of FBC residues in concrete would be economically feasible if their cost to the concrete mix purchaser was about $0.01 (1978 prices) per kg of residue. Based on the above cost plus transportation costs of $0.02 per kkg-km for rail freight and $0.04 per kkg-km for truck haul, FBC residues could be competitive with alternative cement and aggregate materials at distances up to 472 km by rail and 235 km by truck.

5. Substitution of the fluidized-bed residues for part of the aggregate in asphalt did not significantly benefit nor adversely affect the asphalt compression strength. Tests showed that up to 92 percent of the aggregate could be replaced. Based on this percentage, a 5 percent decrease in the cost of asphalt pavements or curb applications could be expected.

6. The use of FBC residues in asphalt would be economically feasible within 250 km by rail (at $0.02/kkg-km) and 125 km by truck (at $0.04/kkg-km) of an FBC power plant (this assumes a Los Angeles, California, 1978 price of $4.96/kkg for asphalt aggregate).

7. Preliminary potting tests to investigate potential agricultural crop application yields, showed that fluidized-bed residues, applied at rates from 2.2 to 11.2 kkg per hectare, can be used beneficially as a soil conditioner when soils are acidic, high in heavy metals, or deficient in trace metals. The height of the tomato plants increased from 15 to 70 percent with the application of the residues.

8. The economic feasibility of using FBC residues to replace slaked lime for elevating soil pH will depend on the alkalinity of the residues. The values of NJFA and NJSBM residues would be $4.80 and $11.80 per kkg, respectively, at a Los Angeles 1978 price of $65 per kkg for slaked lime. At these prices the NJFA and NJSBM residues could be economically competitive at distances up to 240 and 590 km if hauled by rail, and half these distances if hauled by truck.

9. Substitution of FBC residues for calcium carbonate as a source of calcium can be economically feasible for selected crops grown in alkaline soils containing a very high sodium ratio. Tests indicated that the added value of FBC residues relative to calcium carbonate to be $268 per kkg (of which $255 was from increased yield).

10. The fly ash and spent bed materials' high pH (9 to 12) indicated they are usable for neutralizing acid mine drainage. The economic feasibility of reclaiming residues depends on the distance (transportation cost) between the FBC plant and the acid mine drainage, as well as on the cost of alternative landfill disposal (cost of operation and environmental controls near the FBC plant.

11. Since the FBC residues were found useful as an agricultural soil conditioner, they have excellent potential for reclaiming surface-mine spoil areas or other barren land.

12. The fluidized-bed residue can also be reclaimed as a road construction material because of its characteristics. It is also usable for de-icing roads.

13. Fluidized-bed residues are a bulky material, and can be most economically used locally in order to avoid high transportation costs.

14. Fluidized-bed residues have potential as a substitute for commercial lime, dolomite, clay, ashes or inert fill wherever these materials are employed.

CHAPTER 4

RECOMMENDATIONS

1. The pilot-scale test columns study has given valuable information for evaluating the environmental impact of disposing fluidized-bed residues onto land and ocean disposal sites. This work should be expanded to include the investigation and evaluation of the six residues in large-scale field cells, which was originally included in the contract scope of work. The unavailability of sufficient quantities of residues necessitated a postponement of this expanded study; therefore, it is recommended that the field tests be initiated when the fluidized-bed combustion pilot plants operations can provide sufficient residues.

2. Further pilot-scale columns testing, in which the depths of the simulated environments more nearly equal those found under natural conditions, should be conducted. Increasing the heights of the test columns through which the leachate may pass will more nearly duplicate the natural environment leaching characteristics.

3. This report presented preliminary evidence that no two tests, for measuring the leaching characteristics of residues, gave similar results. A detailed study comparing various methods for determining the leaching characteristics of fluidized-bed residues or other potential pollutant materials is needed. In particular, the following should be included in the study; leachate tests for large-scale field cells, small 3-ft square or 5-ft square test plots, and pilot-scale test columns; leaching tests of residues under various quantities of applied water; soluble salt extractions with variable ratios of water to sample; and analyses from the total digestion of the residues.

4. Disposal of fluidized-bed residues onto actual disposal sites should be initiated. Close monitoring of several constituents would be needed to evaluate the impact on the terrestrial environment.

5. Market and field studies to determine the potential marketability of the fluidized-bed residues for different feasible uses should be continued. Uses would include concrete, asphalt, soil cement, acid mine drainage control, and acid mine soil reclamation.

6. The preliminary study in the potential agricultural application of the fluidized-bed residues should be expanded.

7. The toxicity of leachate from fluidized-bed residues disposed in different environments should be further investigated. This can be accomplished by standardized bio assay methods, such as bacteriological counts, biochemical oxygen demand, fish exposure or other procedures.

CHAPTER 5

FLUIDIZED-BED COAL COMBUSTION

Introduction

In fluidized-bed combustion, a granulated bed material (limestone or dolomite) encompasses the pulverized burning coal. In most fluidized bed combustors the bed and fuel are fluidized by fuel injection air and combustion air. The calcareous bed materials absorb sulfur oxides, reducing their emission into the environment. This process generates large quantities of spent dolomite or limestone materials, magnesium, or calcium sulfate, ash and some unburned coal. This sorbent material may be either generated and recycled, or removed from the plants for disposal.

There have been two approaches to steam generation using fluidized-bed boilers. One method uses direct contact between the inert fluidized,heated stone particle bed and the heat transfer surfaces (boiler tubes) to produce steam. An example of a fluidized-bed steam generator with direct contact heat transfer is shown in Figure 1. The hot flue gas, after ash removal, can provide additional heat. In boilers without heat exchange tubes in direct contact with the fluidized-bed, hot off-gases generated all the steam by conventional fashion.

The start-up of an atmospheric fluidized-bed boiler requires heating a portion of the bed to 315° C to ignite the injected coal. After ignition, the temperature of the bed rises until the energy released in the bed equals the energy absorbed by the boiler tubes plus that in the hot gases leaving the bed, and the system achieves normal equilibrium. Excellent heat transfer and high heat capacity is maintained in a fluidized-bed boiler at uniform temperature, typically in the range of 800 to 900° C.

High heat-transfer coefficients between the fluidized-bed and immersed steam generation surfaces reduces the steam tubing requirements and also permits operation at lower and more uniform bed temperatures. The lower temperatures reduces NO_x emissions and slag and decreases equipment corrosion.

Process Descriptions

There are two fluidized-bed combustion modes, with either complete or partial combustion of the fuel. In the complete combustion mode (also called one-step or excess oxygen combustion), oxygen in excess of the stoichiometric quantity required to burn the fuel is fed to the fluidized bed. The oxygen reacts with sulfur, forming sulfur dioxide, which in turn reacts with the calcium or magnesium in limestone or dolomite (hereafter simplified to refer only to the calcium):

$$CaCO_3 + S + 3/2\ O_2 \longrightarrow CaSO_4 + CO_2.$$

In the second mode (called two-step or oxygen deficient combustion), less than the stoichiometric amount of oxygen is added to the fluidized bed. This results in the formation

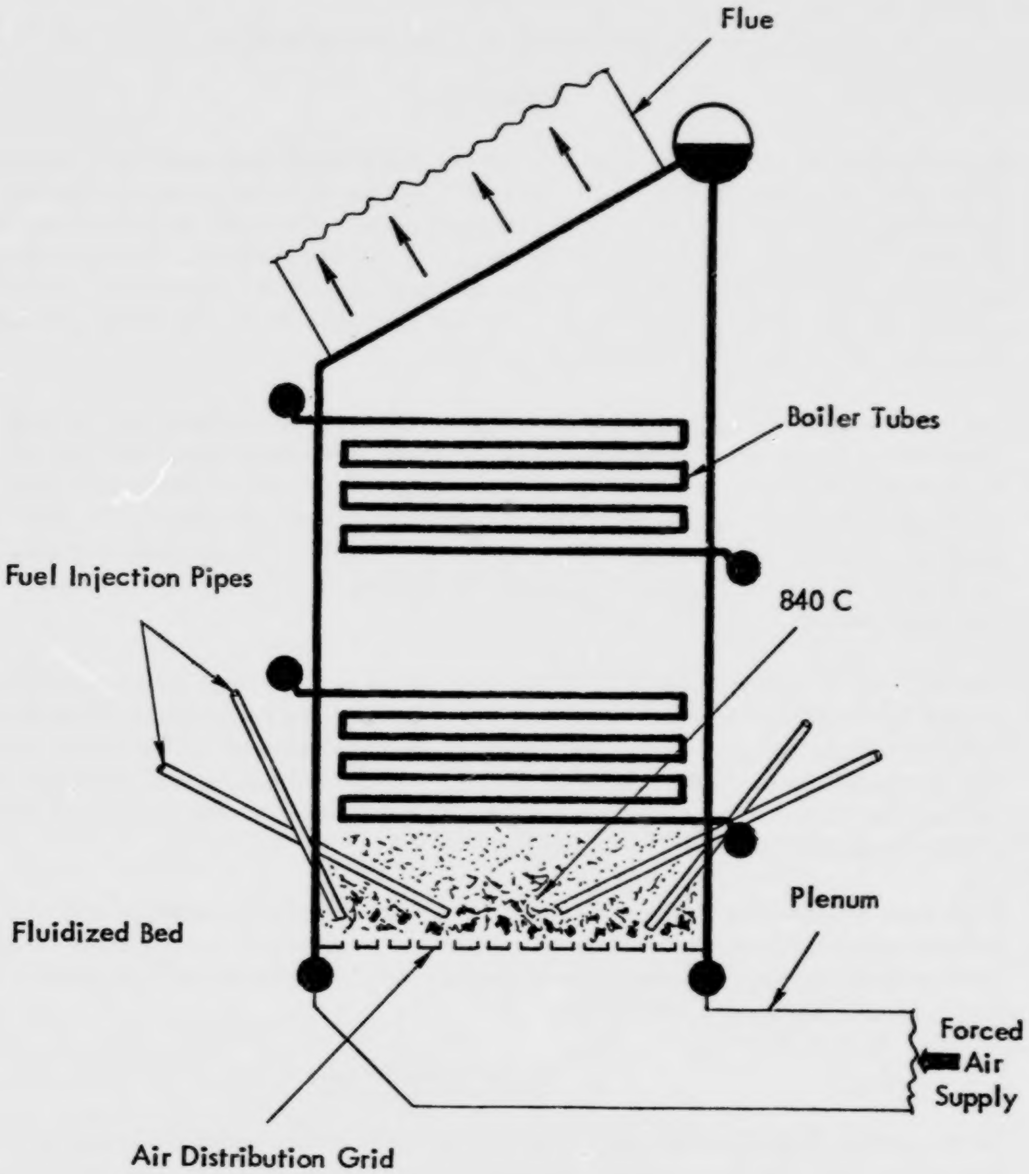

Flue
Boiler Tubes
Fuel Injection Pipes
840 C
Plenum
Fluidized Bed
Forced Air Supply
Air Distribution Grid

Figure 1. Direct contact fluidized-bed steam generator.

Source: 104.

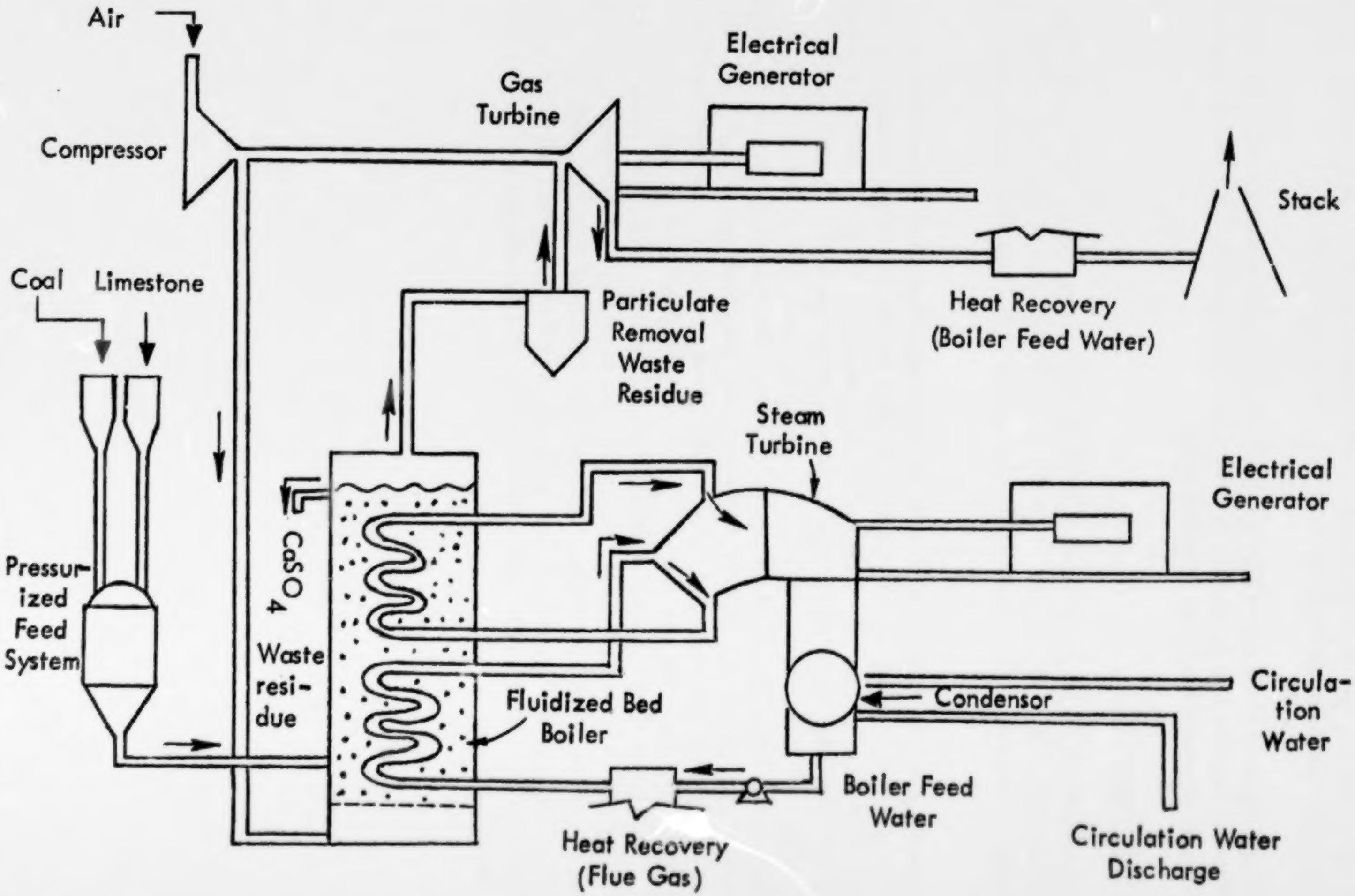
of calcium sulfide (CaS) which can be converted to SO_2 and CaO by roasting it in air or in oxygen, or to $CaCO_3$ and H_2S by reaction with water and CO_2. SO_2 or H_2S can be converted to sulfur (in a Claus plant) or to H_2SO_4 (in an acid plant).

The three basic types of plant operation for the fluidized-bed combustion of coal are: (1) once-through (high or low pressure), (2) one-step regeneration (high or low pressure), and (3) two-step regeneration (high-pressure only).

Once-Through Operation

Once-through operation with pressurized fluid-bed combustion (Figure 2) is quite simple. Calcium sulfate and other compounds are produced in the bed in a stable form which requires disposal. The cost of the process is minimized by operating with maximum sorbent utilization.

Table 7 compares possible alternative fluidized bed combustion plant sorbent processes. The once-through use of limestone or dolomite sorbent results in greater amounts of waste residues than if these residues were regenerated and recycled; however, with the present state-of-the-art, residues regeneration appears to be uneconomical. Approximately 7 times, by-weight, of raw crushed dolomite is needed for each unit of coal burned in a fluidized bed unit. Table 7 indicates that the fluidized bed process generates by weight, about 3 times as much spent bed residue as fly ash, and the total quantity of fluidized bed residues represents the total of the original dolomite or limestone sorbent plus the solid ashes from the burned coal and the chemical combination of sulfur and other reactive materials. The total weight of residues from the fluidized bed combustion process noted in Table 7 is estimated to be 1,958 kkg/day versus the total input of 195 plus 1,410 kkg/1 hour of coal and dolomite respectively. Detailed description of the fluidized bed combustor units is presented in Appendix D. In addition, the fluidized-bed oil gasification process, including the Chemically Active Fluid-Bed (CAFB),developed by Esso, is described in Appendix E.


Air
Compressor
Gas
Turbine
Electrical
Generator
Stack
Coal
Limestone
Particulate
Removal
Waste
Residue
Heat Recovery
(Boiler Feed Water)
Steam
Turbine
Electrical
Generator
Pressurized
Feed
System
$CaSO_4$
Waste
residue
Fluidized Bed
Boiler
Condensor
Circulation
Water
Boiler Feed
Water
Heat Recovery
(Flue Gas)
Circulation Water
Discharge

Source: 104.

Figure 2. Once-through pressurized fluidized bed boiler power plant.

TABLE 7. COMPARISON OF FBC SORBENT PROCESSES

Impact	One Step - 10 atm 1% SO_2		One Step - 10 atm 2% SO_2		One Step-1 atm 10% SO_2		Two Step		Once Through	
	A[b]	B[b]	A[b]	B[b]	A[b]	B[b]	A[b]	B[b]	A[c]	B[d]
Energy										
Plant heat rate[e] (kcal/kwhr)	2,600	2,700	2,470	2,550	2,360	2,390	2,460	2,520	2,330	2,290
Plant energy cost (mills/kwhr)	13.88	14.61	13.21	13.67	13.13	13.59	13.94	14.67	13.45	12.30
Raw materials[f]										
Total coal input (kkg/hr)	221	229	211	216	202	205	212	218	195	195
Dolomite input (kkg/hr)	940	940	940	940	940	940	940	940	2,830	1,410
Methane input (10^3 cu m /day) at STP	790	103	75	97	69	90	0	0	0	0
Plant residues										
Spent bed material (kkg/day)	807	698	807	698	807	698	980	970	2,450	1,490
Ash output[g]	531	549	508	518	485	492	510	522	468	468
Sulfur output (kkg/day)	143	149	137	141	124	125	139	141	0	0
Sulfur removal efficiency[h] (%)	90	90	90	90	85	85	90	90	94	94
Increase in U.S. coal production relative to once through operation for total conversion to regenerative FBC processes (%)	13.3	17.3	8.1	10.5	3.8	4.9	9.0	11.7	--	--
U.S. limestone/dolomite production required for complete conversion to fluidized bed combustion (%of present total)	10	10	10	10	10	10	10	10	30	15

(continued)

CHAPTER 6

RESIDUE CHARACTERIZATION

Purpose

The purpose of this subtask was to determine the chemical and physical properties of FBC residue samples and the stratum materials used in pilot scale column studies. This provided a preliminary screening of potential environmental effects and direction of subsequent efforts. The results were used in planning and conducting the pilot-scale column studies of residue disposal and in testing commercial and agricultural applications.

Residue Characteristics

The chemical composition of ash and spent bed material was dictated, to a large extent, by the composition of the bed material and the fuel. Natural materials were largely impure, and both coal and oil as well as limestone and dolomite contained variable traces of most metals. Combustion and other high temperature reactions produced ashes and spent bed material containing many of these trace metals. The specific chemical composition of a given ash or spent bed material was dependent on the combustion parameters (including the pressure), the fuel, and the bed material; and, as a result, the composition of ash and bed material varied widely.

All of the residue samples available to us were from the pilot plant test runs and may not be representative of future production runs. Where possible, we determined the actual pilot plant test operating conditions and obtained analyses of the raw fuel and sorbent feeds. (See Table 8.) Given this latter information, it was possible to relate our test results to future production conditions.

Tables 9 through 11 give available analyses of coal and limestone feeds provided by some of the experimental plants. The composition of fossil fuels used in these experiments varied widely. The percentages of sulfur in the coal ranged from 0.75 to 4.46, and about 1.28 in the coke (on a dry basis). Venezuelan No. 6 oil, used in the Esso gasifier, had a sulfur content of about 2.5 percent.

The percentage of calcium in the PER limestone was 36, and 47.5 for Greer and Germany Valley, respectively. Available data showed that the sulfur content of the limestones was 0.3 percent for Greer and 0.15 percent for the Germany Valley limestones. Magnesium, iron, aluminum and silicon were other important constituents in the limestones. Probably both limestone and coal contained several trace metals, but available data showed only 0.89 percent titanium in the coal used for the PER plant. Unfortunately, not all the experimental plants that supplied residues were able to provide complete chemical analysis or other descriptive information about the raw materials that were used.

TABLE 8. PILOT PLANT OPERATION FOR CHARACTERIZED RESIDUES

Residue Source	Run No.	Temp. °C	Excess Air Vol. %	Fuel Type	Sulfur %	Bed Sorbent	Ca/S molar feed ratio	Flue SO_2 ppm
Pope, Evans & Robbins Alexandria, Va. Fly ash Spent bed material	N.A.[*]	815 to 870	18	High sulfur bituminous coal Sewickley, Pa.	4 to 4.5	Calcined limestone Germany Valley & Greer, W. Va.	Variable	Variable
Exxon Miniplant Linden, N. J. Fly ash Spent bed material	30.4	835 (avg.)	16.1	Illinois N6	4.2 to 4.8	Grove limestone	3.7	894
Esso CAFB Abingdon, England Cyclone fly ash Fines, stack fly ash Spent bed material	10	860 to 950	N.A.[a]	No. 6 heating oil Venezuela	2.5	Lime BCR1359 U.S.A.	1 (avg.)	200

[a] N. A. = Not Available.

TABLE 9. CHARACTERIZATION OF POPE, EVANS, AND ROBBINS BITUMINOUS COAL SAMPLES (percentage by weight)

Constituent	Coal	Coke[a]	Ash
Ash	17.44	27.82	100.0
Volatiles	37.31	0.00	0.0
Fixed carbon	45.25	72.18	0.0
	100.00	100.00	100.0
Pyritic sulfur	3.04	0.00	0.0
Sulfate sulfur	0.18	0.29	1.0
Organic sulfur	1.24	0.99	0.0
Total sulfur	4.46	1.28	1.0
Carbon	67.56	76.18	0.0
Hydrogen	4.80	0.00	0.0
Nitrogen	0.93	0.00	0.0
Sulfur	4.46	1.28	1.0
Silicon	4.08	6.51	23.4
Iron	2.48	3.96	14.2
Aluminum	1.80	2.87	10.3
Calcium	0.63	1.00	3.6
Magnesium	0.10	0.16	0.6
Potassium	0.38	0.61	2.2
Sodium	0.10	0.16	0.6
Titanium	0.09	0.14	0.5
Oxygen	12.59	11.3	43.6
	100.00	100.00	100.0

[a] Calculated values.

"Personal Communication, Robert R. Reed, Pope, Evans and Robbins, Inc. to Ralph Stone, Ralph Stone and Company, Inc., March 23, 1976."

TABLE 10. CHARACTERIZATION OF POPE, EVANS, AND ROBBINS LIMESTONE SAMPLES (percentage by weight)

Constituent	Greer Limestone	Germany Valley Limestone
Calcium carbonate ($CaCO_3$)	75.0	98.3
Magnesium carbonate ($MgCO_3$)	4.0	0.5
Ferric oxide (Fe_2O_3)	0.75	0.2
Alumina (Al_2O_3)	3.3	0.5
Silica (SiO_2)	9.5	0.6
Sulfur (S)	0.3	0.15

"Personal Communication, Robert R. Reed, Pope, Evans and Robbins, Inc. to Ralph Stone, Ralph Stone and Company, Inc. March 23, 1976"

TABLE 11. CHARACTERIZATION OF EXXON MINIPLANT COAL SAMPLES (percentage by weight)

Constituent	As Analyzed	Dry	After Ignition
Moisture	3.3	--	--
Ash	9.95	10.26	--
Volatiles	10.00	10.31	--
Carbon	67.71	69.81	77.79
Hydrogen	4.77	4.92	5.48
Nitrogen	1.17	1.21	1.34
Oxygen	9.19	9.47	10.55
Chlorine	0.05	0.05	0.06
Sulfur	4.20	4.33	4.83

"Personal Communication. R.C. Hoke, Exxon Research and Engineering Co., to Ralph Stone, Ralph Stone and Company, Inc. March 19, 1976."

Experimental Procedures

Chemical Composition

The preliminary chemical tests of the residue samples consisted of: 1) characterization after perchloric acid digestion; 2) determination of their water, basic, and acid soluble fractions, and 3) determination of their sequential water leaching characteristics. All the analyses were conducted according to EPA Methods for Chemical Analysis of Water and Wastes and Standard Methods, 14th ed. Appendix A of this report gives methods and references for each analysis.

Total Residue Digestion. The total chemical compositions of the residue samples were determined after perchloric acid digestion. One gram residue samples were digested according to the procedure referenced in Appendix A. The only significant departure from this procedure was the use of nickel instead of platinum utensils; therefore, total nickel analysis was not performed.

Soluble Salt Extraction. The solutions to be analyzed were prepared by placing 100 g samples of each type of residue, as received, in a flask and adding either 250 ml of distilled water, 1.0 N NaOH, or 1.0 N HNO_3 in accordance with EPA-recommended procedures as further described in Appendix A. After mixing for twenty-four hours, the solutions were filtered and the filtrate analyzed to determine the constituents in the acid, base, and water soluble residue extraction, including pH, COD, BOD, and TDS.

The BOD_5 analyses were performed on the water extracts and on distilled water samples. The extract and distilled water samples contained 6.5 percent of a nutrient solution of glucose, peptone, calcium chloride, magnesium sulfate, ammonium chloride, sodium phosphate, potassium phosphate, and ferric chloride.

Residue Leaching Tests. Preliminary bench-scale leaching tests were conducted in the laboratory on residue samples prior to the construction of the pilot-scale test columns. The purpose of these accelerated tests was to estimate the long-term leaching characteristics of the residues. Two hundred and fifty gram samples of each residue were placed in 30.48-cm high and 5.08-cm ID plastic columns. Figure 3 illustrates the column operations. The six volumes of water was added at the rate of 250 ml per leaching cycle. For the NJFA, NJSBM, VFA, and VSBM, leachate was collected by gravity percolation once a week for six weeks. For the residues from Esso, Great Britain, accelerated small-scale column leaching was also developed to simulate 52 separate 250 ml leaching cycles in a period of several weeks.

Bench-scale leaching studies were also conducted on the various stratal materials used in the large-scale test columns. Table 12 lists the types and quantities of materials tested. Three 250 ml leaching cycles were done using the procedures described above. Chemical analyses were conducted to determine the quantities of various constituents leached out of these materials over time. These values were then used to help establish background or baseline concentrations of leachate constituents analyzed in the pilot-scale columns.

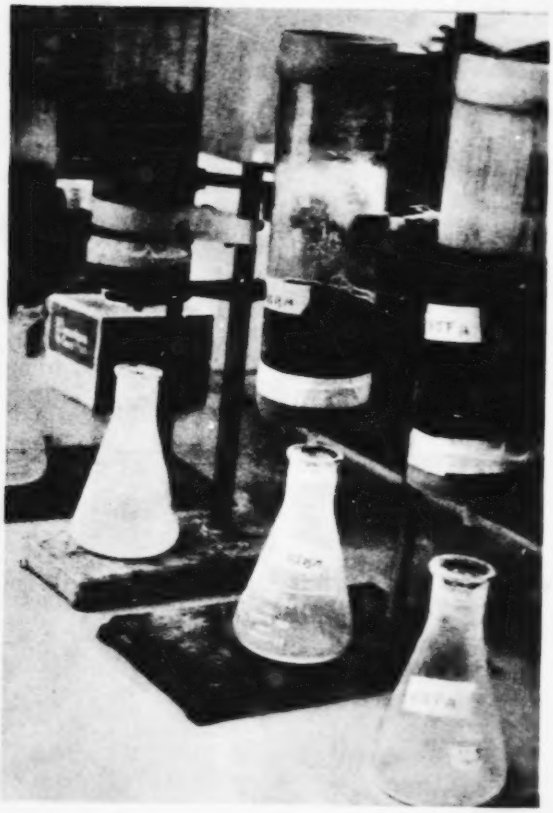


Figure 3. Laboratory-scale column leaching.

TABLE 12. STRATIGRAPHIC MATERIALS SIMULATED IN LEACHING TESTS

Stratigraphic Unit	Simulant Material	Quantity (g)
Sandstone	#16 Silica sand	300
Sandstone	#60 Silica sand	300
Claystone	#60 Silica sand clay (kaolin)	240 60
Dolomite	Coarse meal grade dolomite	300
Limestone	Coarse meal grade limestone	300
Granite bedrock	Granitic pea - gravel Decomposed granite	225 75
Bituminous coal	Coarse ground lump bituminous coal	100

Chemical Properties

Acid Neutralization Capacity. The test involved dissolving a weighted amount of residue in distilled, deionized water. As measured quantities of 12N HCL were added, the pH was monitored until the neutral value was reached. The results were calculated to equivalents of 1 N HCL required to neutralize one kg of residue.

Cation Exchange Capacity. The cation exchange capacities of the residues and stratal materials were measured to indicate the amount of interchange that could occur as a result of leachate water moving through the various strata in the test columns. The existing cations were replaced with sodium ions in an acetate solution. The sodium ions were then replaced by ammonium ions in the acetate solution. The concentration of sodium ions in the ammonium acetate was measured next and converted to cation exchange capacity in milliequivalents per 100 g of original dry material. A detailed outline of the procedure is referenced in Appendix A.

Slaking Test. One feature of some of the pilot plant residues, as received was their extreme exothermal activity upon addition of water. The primary cause was lime slaking:

$$CaO + H_2O \longrightarrow Ca(OH)_2 + \text{heat.}$$

The slaking test involved measuring the amount of heat released from each residue material. After a 3.8 liter volume of water was added to 13.6 kg of residue, the mixture was continually stirred, and the rise in temperature was recorded.

Physical Properties

Residue samples to be slaked were covered with water and allowed to react. When all activity had ceased, the slaked samples were dried in an oven at approximately 103° C for 24 hours. Unslaked residue samples were used as received without further drying since moisture content was already about zero.

Particle Size Analysis. The procedure used complied with ASTM D422 as referenced in Appendix A. A 500 g sample of each slaked and unslaked residue was sieved, using a number 4, 10, 20, 40, 80, 100, and 200 sieves. Hydrometer analyses were not performed on spent bed materials because the residues were partially soluble. Hydrometer analyses were conducted on slaked samples for the fly ashes.

Specific Gravity. Specific gravity measurements were made for test residues to establish their physical characteristics for aggregate or other possible uses. The method used was that shown in ASTM D854 (see Appendix A), except that step 6.2 was changed from a period of partial vacuum to a period of vigorous shaking. This did not affect the results. Specific gravity values were not obtained for the spent bed materials, as some portions were soluble and this phenomenon interfered with the ASTM D854 type analysis.

Moisture Content. The moisture content of the residues, as received, were determined by following the procedures in ASTM D2216, as referenced in Appendix A.

Degree of Saturation

Degree of saturation was obtained by substituting into the formula:

$$S = \frac{WG}{G\left[(1/w) - (1/d)\right] - 1}, \text{ where}$$

W = moisture content	1/w = unit weight of water
G = specific gravity	1/d = unit weight of residue

Loose Dry Density. The dry density of each residue, both slaked and unslaked, was determined by pouring the dried residue into a 100-ml beaker. The difference between the empty and filled weights of the container was divided by the known volume to yield the loose dry density value.

Water-holding Capacity. Water-holding capacity was determined for the slaked residues only. A sample of slaked and dried residue was placed in a funnel lined with filter paper, covered with water, and allowed to drain under the force of gravity. The sample, covered to prevent evaporation, was allowed to stand until there was no further drainage for a five-minute period. Then, the wet sample was weighed, dried at approximately 103° C for 24 hours, and reweighed. The difference between the wet and dry weights was equal to the water held in the sample. This was divided by the dry weight of the sample to give the water-holding capacity of the residues.

Permeability. Data was obtained following the procedure described in the Standard Method of Test for Permeability of Granular Soils (Constant Head); see Appendix A.

Results

Chemical Composition

Total Residue Digestion. The results of the total perchloric acid digestion of the fluidized-bed are shown in Table 13. The residues obtained from Exxon, Linden, New Jersey, and from Pope, Evans, and Robbins, Alexandria, Virginia, contained high levels of aluminum and iron. In fact, the iron content ranged from 1 to 7 percent of the total.

TABLE 13. TOTAL DIGESTION CHARACTERISTICS OF FLUIDIZED-BED RESIDUES

Constituent[a]	Fluidized-Bed Residue Type					
	NJFA	NJSBM	VFA	VSBM	EFA	ESBM
Aluminum	5,800	960	3,600	3,840	240	N.D.
Arsenic	0.2	< 0.1	< 0.1	0.3	N.D.[b]	0.4
Barium	40	120	200	120	160	520
Cadmium	2.8	4.0	0.8	2.4	1.6	2.4
Chromium	292	192	228	205	176	152
Copper	152	168	164	225	180	148
Iron	11,030	1,830	7,390	4,070	48	N.D.
Lead	40	32	20	28	24	16
Magnesium	6,290	2,530	300	585	375	1,895
Manganese	650	475	165	315	120	215
Molybdenum	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Potassium	7,200	5,600	8,400	19,400	6,000	11,400
Sodium	80	72	112	192	64	144
Zinc	92	92	80	208	32	28

[a] All values are reported as mg constituent/kg residue.

[b] N.D. - not detected.

The residues from Esso, Great Britain, however, contained relatively little aluminum and iron. The NJFA, NJSBM, and ESBM contained from 2,000 to 6,000 mg/kg of magnesium while the magnesium content ranged from 120 to 315 mg/kg in the VFA, VSBM, and EFA. The residues contained similar quantities of the other metals which were analyzed.

Soluble Salt Extraction. The laboratory extraction tests wherein residue was added to water, an acidic solution, and a basic solution, to characterize their soluble fractions are presented in Tables 14 through 17. The BOD results are shown graphically in Figure 14.

Results of the tests for residue characterization showed water soluble fractions in NJFA were higher than acid soluble fractions for boron and magnesium, and higher than base soluble fractions for nitrate. Water soluble fractions in NJSBM were higher than acid soluble fractions for sulfate, boron, lead, magnesium, and sodium, and higher than base soluble fractions for nitrate, aluminum, calcium, copper, manganese, and molybdenum.

Water soluble fractions in VFA were higher than acid soluble fractions for sulfate, boron, lead, and sodium, and higher than base soluble fractions for nitrate, calcium, copper, magnesium, manganese, molybdenum, and nickel. For VSBM, the water soluble fractions exceeded acid soluble fractions for sulfate, boron, and sodium, and exceeded base soluble fractions for nitrate, aluminum, boron, calcium, copper, magnesium, manganese, and molybdenum.

All the constituents in the EFA, except chloride, nitrate, and phosphate, were less in the water soluble fraction than in the acid soluble fractions. The water soluble fraction exceeded the base soluble fraction for chloride, nitrate, phosphate, aluminum, calcium, chromium, iron, lead, manganese, molybdenum, silver, and zinc ions. For the ESBM, the acid soluble fractions exceeded the water soluble fractions for all the constituents except sulfate, boron, and molybdenum, and the water soluble fractions exceeded the base soluble fractions for all the constituents except sulfate, aluminum, arsenic, beryllium, magnesium, and zinc.

CFA water soluble fractions were less than acid soluble fractions for all constituents and exceeded base soluble fractions for nitrate, aluminum, calcium, iron, magnesium, manganese, molybdenum, silver, and zinc. FSFA water soluble fractions exceeded acid soluble fractions for nitrate, arsenic, boron, cadmium, calcium, iron, lead, magnesium, molybdenum, and silver. Due to a shortage of residues for analysis, some acid and base soluble fractions were not determined.

Comparisons of the results from the soluble salt extraction test shows that the solubility of certain constituents are greatly affected by pH. That is, low pH generally increased the solubility of heavy metals and greatly increased the calcium content by 2,000 to 4,000 percent. The increased solubility of the calcium in the acid extraction may have been caused by the reaction of insoluble calcium salts with the 1.0 N HNO_3 used for acidifying the samples. The solubility of calcium nitrate was found to be 122 grams per 100 ml of water at 18° C; whereas the sulfate and carbonate salts of calcium were relatively insoluble. Acidification may also have caused the calcium to leach out as calcium chloride, another

TABLE 14. SOLUBLE SALT EXTRACTION CHARACTERIZATION OF RESIDUES[a]

1. EXXON MINIPLANT, LINDEN, NEW JERSEY

	Fly Ash			Spent Bed Material		
Constituent	Water Soluble	Acid[b] Soluble	Base[c] Soluble	Water Soluble	Acid[b] Soluble	Base[c] Soluble
pH	9.3	<1.0	13.0	12.2	6.6	13.0
Total dissolved solids	2,124	--[e]	--	4,188	--	--
COD	45.6	--	--	51.4	--	--
BOD	--[f]	--	--	--[f]	--	--
Chloride	ND[d]	ND	5.76	ND	ND	8.42
Nitrate	27	--	3	26	--	ND
Phosphate	4	182	6.3	ND	1.5	ND
Sulfate	1,190	5,300	26,000	1,900	1,000	17,400
Aluminum	--	--	--	0.06	0.26	ND
Arsenic	ND	--	--	--	--	--
Beryllium	--	--	--	ND	ND	ND
Boron	0.61	ND	0.88	0.64	ND	ND
Cadmium	ND	0.2	0.2	ND	0.5	0.97
Calcium	1,805	34,600	ND	6,017	96,754	ND
Chromium	--	--	--	--	--	--
Copper	--	--	--	0.5	1.07	0.12
Iron	ND	78.4	1.6	ND	7.6	1.8
Lead	2.5	7.7	6.0	2.4	1.4	5.9
Magnesium	10	ND	2,360	95	ND	3,200
Manganese	--	--	--	0.025	0.95	ND
Molybdenum	ND	69	ND	12	278	ND
Nickel	--	--	--	0.5	7.7	0.75
Potassium	24	440	--	32	248	--
Silver	ND	0.2	0.4	0.02	0.6	0.3
Sodium	22	400	--	89	ND	--
Zinc	ND	8.0	0.5	ND	1.0	0.2

[a] All concentrations in mg constituent/kg residue, dry weight after extraction (24 hr. shake test).

[b] 1.0 N HNO_3.

[c] 1.0 N NaOH.

[d] None detected = ND.

[e] -- Analysis not performed.

[f] See Figure 11.

TABLE 15. SOLUBLE SALT EXTRACTION CHARACTERIZATION OF RESIDUES[a]
II. POPE, EVANS, & ROBBINS, ALEXANDRIA, VIRGINIA

	Fly Ash			Spent Bed Material		
Constituent	Water Soluble	Acid[b] Soluble	Base[c] Soluble	Water Soluble	Acid[b] Soluble	Base[c] Soluble
pH	12.2	4.1	12.9	12.2	6.1	12.9
Total dissolved solids	4,212	--[e]	--	4,064	--	--
COD	104.6	--	--	57.8	--	--
BOD	--[f]	--	--	--[f]	--	--
Chloride	ND[d]	ND	6.21	ND	ND	22.83
Nitrate	2	--	ND	28	--	7
Phosphate	ND	2	ND	ND	ND	ND
Sulfate	1,600	1,050	17,400	1,640	1,050	32,500
Aluminum	ND	1.2	ND	0.06	0.26	ND
Arsenic	--	--	--	--	--	--
Beryllium	ND	ND	ND	ND	ND	ND
Boron	0.5	ND	0.83	0.82	ND	0.72
Cadmium	ND	0.5	0.2	ND	0.5	0.3
Calcium	540	32,000	ND	750	32,000	ND
Chromium	--	--	--	--	--	--
Copper	0.025	0.92	ND	0.5	1.07	0.12
Iron	0.5	11.0	1.7	0.1	6.6	2.2
Lead	1.6	1.3	7.1	1.1	1.5	7.6
Magnesium	96	1,940	10	22	22	ND
Manganese	0.025	0.87	ND	0.025	0.95	ND
Molybdenum	10	247	ND	11	272	7
Nickel	0.25	7.7	ND	0.5	7.7	0.75
Potassium	33	276	--	63	276	--
Silver	0.08	0.7	0.3	0.08	0.8	0.4
Sodium	145	ND	--	178	100	--
Zinc	0.08	1.1	1.0	ND	0.3	0.4

[a] All concentrations in mg constituent/kg residue, dry weight after extraction (24 hr shake test).

[b] 1.0 N HNO_3.

[c] 1.0 N NaOH.

[d] None detected = ND.

[e] -- Analysis not performed.

[f] See Figure 11.

TABLE 16. SOLUBLE SALT EXTRACTION CHARACTERIZATION OF RESIDUES[a]
III. ESSO, GREAT BRITAIN

	Fly Ash			Spent Bed Material		
Constituent	Water Soluble	Acid[b] Soluble	Base[c] Soluble	Water Soluble	Acid[b] Soluble	Base[c] Soluble
pH	12.2	2.4	12.9	12.1	10.8	12.9
Total dissolved solids	5,266	--[e]	--	6,214	--	--
COD	132	116	98	68	68	59
BOD	f	--	--	f	--	--
Chloride	11,200	5,000	10,000	8,200	12,500	10,280
Nitrate	24.5	--	ND[d]	12	--	9.4
Phosphate	6.0	2.0	1.0	1.9	1.9	0.6
Sulfate	4,380	2,625	24,310	3,380	250	4,625
Aluminum	0.25	1.75	ND	0.25	1.25	1.0
Arsenic	ND	0.05	ND	ND	0.1	ND
Berryllium	ND	ND	42	ND	50	114
Boron	ND	0.325	ND	0.63	ND	0.52
Cadmium	ND	0.075	0.05	0.05	0.28	ND
Calcium	4,500	70,000	316	4,750	75,000	60
Chromium	1.75	14.2	ND	1.5	13.5	ND
Copper	ND	2.25	ND	0.5	2.0	ND
Iron	1.0	7.0	0.25	1.7	6.0	ND
Lead	0.075	ND	ND	0.17	ND	ND
Magnesium	1.0	1.3	1.0	1.0	1.3	1.0
Manganese	0.075	0.75	0.025	0.1	0.6	ND
Molybdenum	81	180	ND	0.8	ND	ND
Nickel	1.25	8.0	1.5	0.25	7.5	ND
Potassium	52	232	--	ND	ND	--
Silver	0.20	0.68	0.15	0.08	0.72	ND
Sodium	245	270	--	40	45	--
Zinc	0.15	0.3	0.025	0.15	0.30	ND

[a] All concentrations in mg constituent/kg residue, dry weight after extraction (24 hr shake test).
[b] 1.0 N HNO_3.
[c] 1.0 N NaOH.
[d] None detected = ND.
[e] -- Analysis not performed.
[f] See Figure 11.

TABLE 17. SOLUBLE SALT EXTRACTION CHARACTERIZATION OF RESIDUES[a]

IV. ESSO, GREAT BRITAIN

	Fly Ash[d]			Fly Ash[e]		
Constituent	Water Soluble	Acid[b] Soluble	Base[c] Soluble	Water Soluble	Acid[b] Soluble	Base[c] Soluble
pH	12.1	6.2	12.9	12.0	6.4	13.0
Total dissolved solids	3,808	--[g]	--	4,380	--	--
COD	197.6	--	--	252.3	--	--
BOD	--[h]	--	--	--[h]	--	--
Chloride	199.5	210.6	354.6	160.7	77.6	388.0
Nitrate	11.8	--	ND[f]	10.6	--	2.6
Phosphate	1.87	--	--	0.35	--	--
Sulfate	1,280	2,000	11,300	1,680	2,190	3,260
Aluminum	0.25	1.75	ND	--	--	--
Arsenic	0.1	3.7	0.3	0.1	3.4	ND
Beryllium	ND	ND	42	--	--	--
Boron	ND	ND	0.13	0.43	ND	0.07
Cadmium	ND	0.18	0.01	0.01	0.18	ND
Calcium	510	32,000	ND	520	32,000	ND
Chromium	--	--	--	--	--	--
Copper	ND	2.25	ND	--	--	--
Iron	0.46	5.23	0.25	0.43	4.78	ND
Lead	0.5	5.2	0.7	0.6	5.3	0.1
Magnesium	7	16	ND	5	13	ND
Manganese	0.075	0.75	0.025	--	--	--
Molybdenum	17	229	ND	12	2.7	ND
Nickel	1.25	8	1.5	--	--	--
Potassium	56	356	--	62	276	--
Silver	0.04	0.53	ND[f]	0.03	0.50	ND
Sodium	300	800	--	200	200	--
Zinc	0.03	0.13	ND	ND	0.10	ND

---

[a] All concentrations in mg constituents/kg residue, dry weight after extraction (24 hr shake test)"

[b] 1.0 N HNO_3.

[c] 1.0 N NaOH.

[d] Cyclone fly ash.

[e] Fines, stack fly ash.

[f] None detected = ND.

[g] -- Analysis not performed.

[h] See Figure 11.

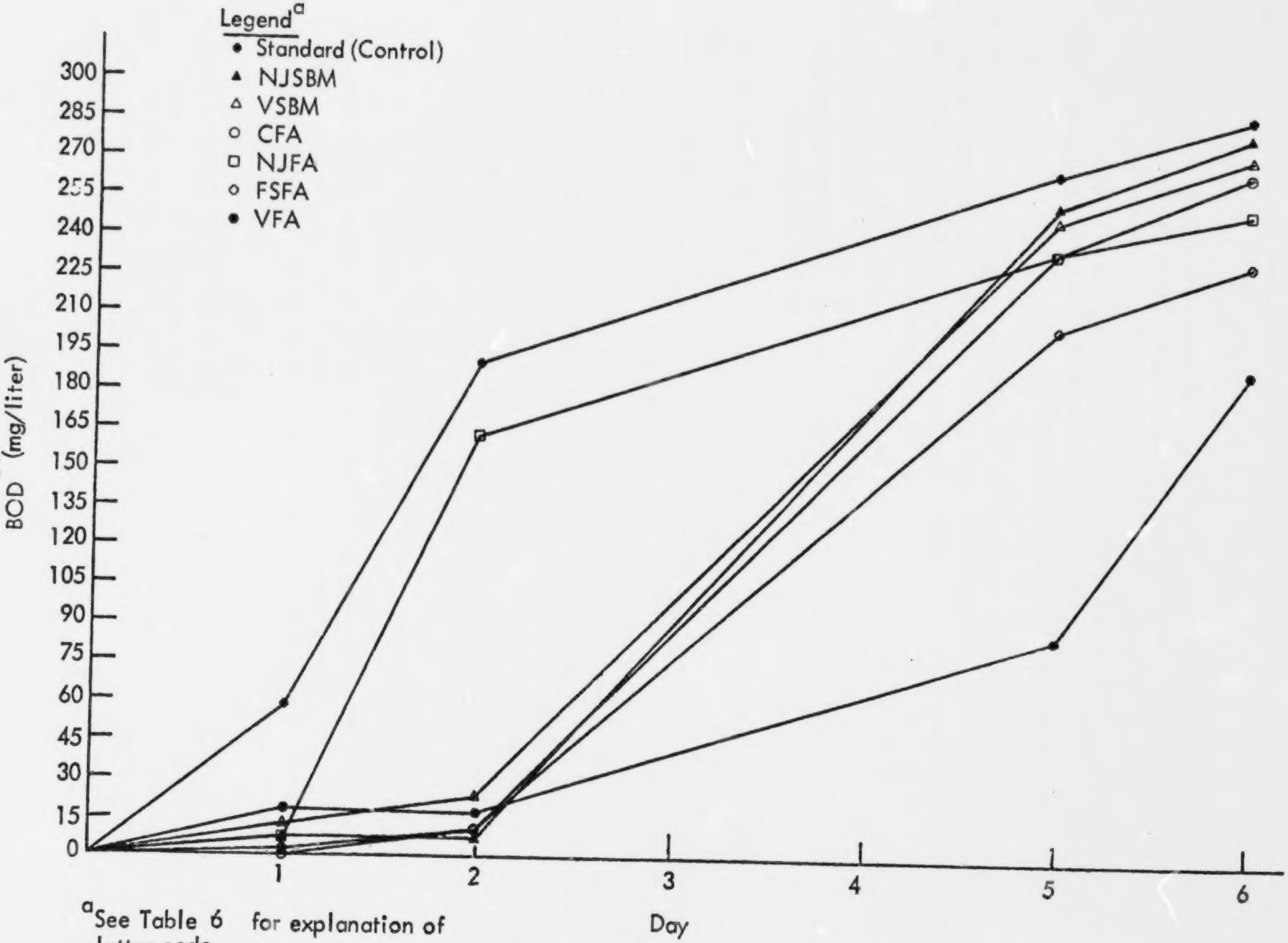


Figure 4. BOD from residue water extracts.

[a] See Table 6 for explanation of letter code.

quite soluble calcium salt. High pH was found to have greatly increased the solubility of sulfate and magnesium. Comparison of the results also showed that EFA and ESBM were much higher in chlorides.

The BOD_5 test was used to measure the biochemical rate of decomposition of the residues' water extracted samples. The solutions with added residues showed a lag time of two days during which the BOD was inhibited. After the second day, the BOD of each residue sample increased so that the 5-day biochemical oxygen demand was nearly as high as the control sample. The results indicated that the leachates contained constituents which acted as temporary inhibitors to microorganism growth.

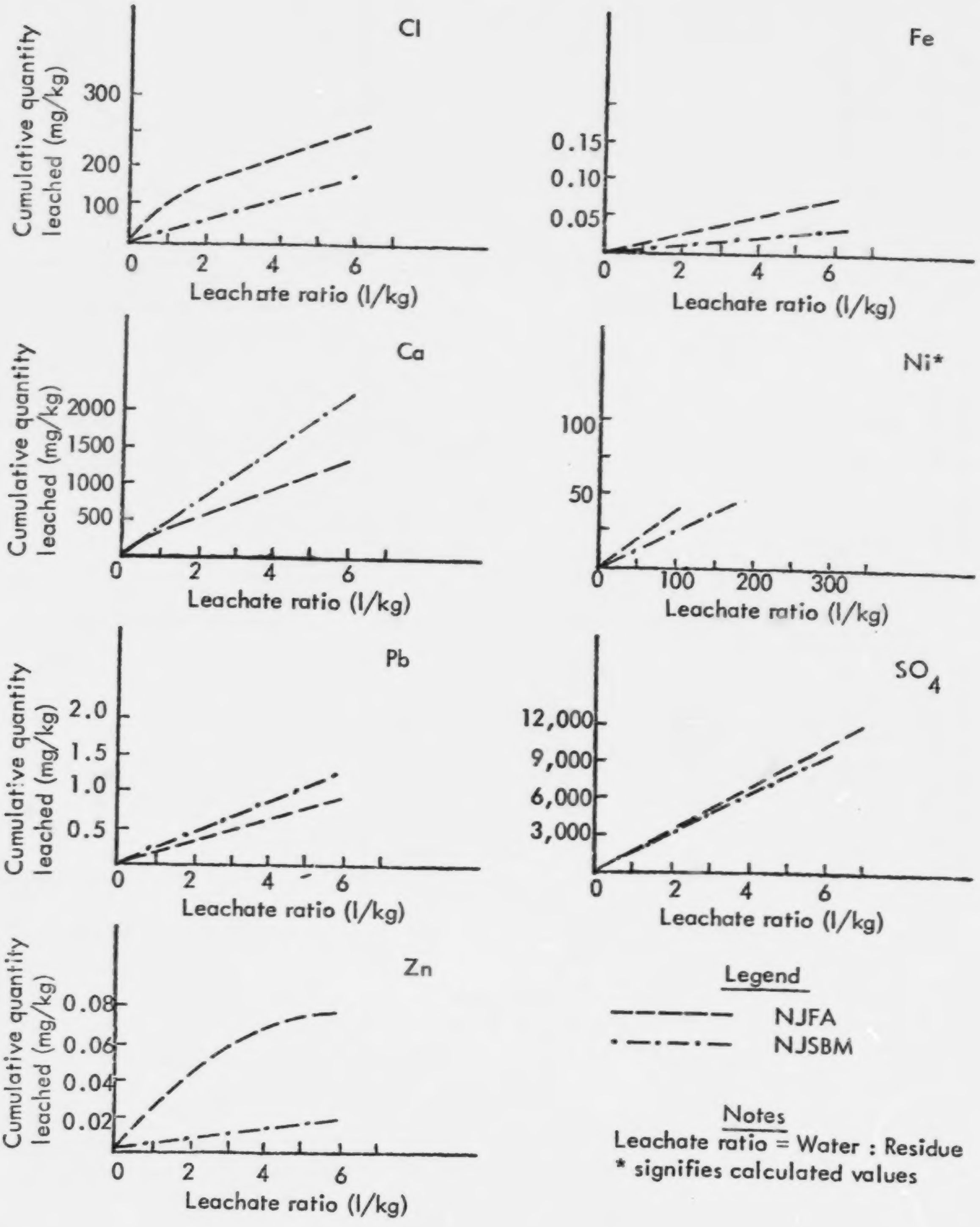
Residue Leaching Test. The results of the accelerated residue leaching tests are shown in Figures 5 to 7. Chlorides from NJFA and NJSBM, sulfates, calcium, iron, nickel, lead, and zinc (except from NJFA), were leached at a relatively constant rate. The constituents extracted from the EFA and ESBM maintained a fairly constant rate of leaching even after 100 liters of water per kilogram of residue passed through the bench scale columns. The chlorides from VFA, and VSBM, and the zinc from NJFA were nearly completely leached from the residues after six times the residues' weight of water had passed through the columns. All the constituents leached from the residues were extracted readily.

The results of the bench-scale leaching test for the stratal materials are listed in Tables 18 to 24. All the stratal materials were leached. The stratal materials contained substantial quantities of sulfate (except the limestone and dolomite) and sodium. Nearly all the sulfate was leached after 750 ml was passed through the columns; whereas, only a fraction of the sodium appeared to have been extracted. The limestone leachate contained traces of cadmium and potassium, while traces of arsenic, calcium, lead, and potassium were leached from the dolomite sample. Traces of arsenic, calcium, and lead were found in the bituminous coal; and the granite bedrock stratal material contained traces of arsenic and calcium. The #16 and #60 silica sand leached chlorides and potassium, while chlorides and traces of arsenic, calcium, iron, and magnesium were found in the claystone leachate.

Chemical Properties Tests

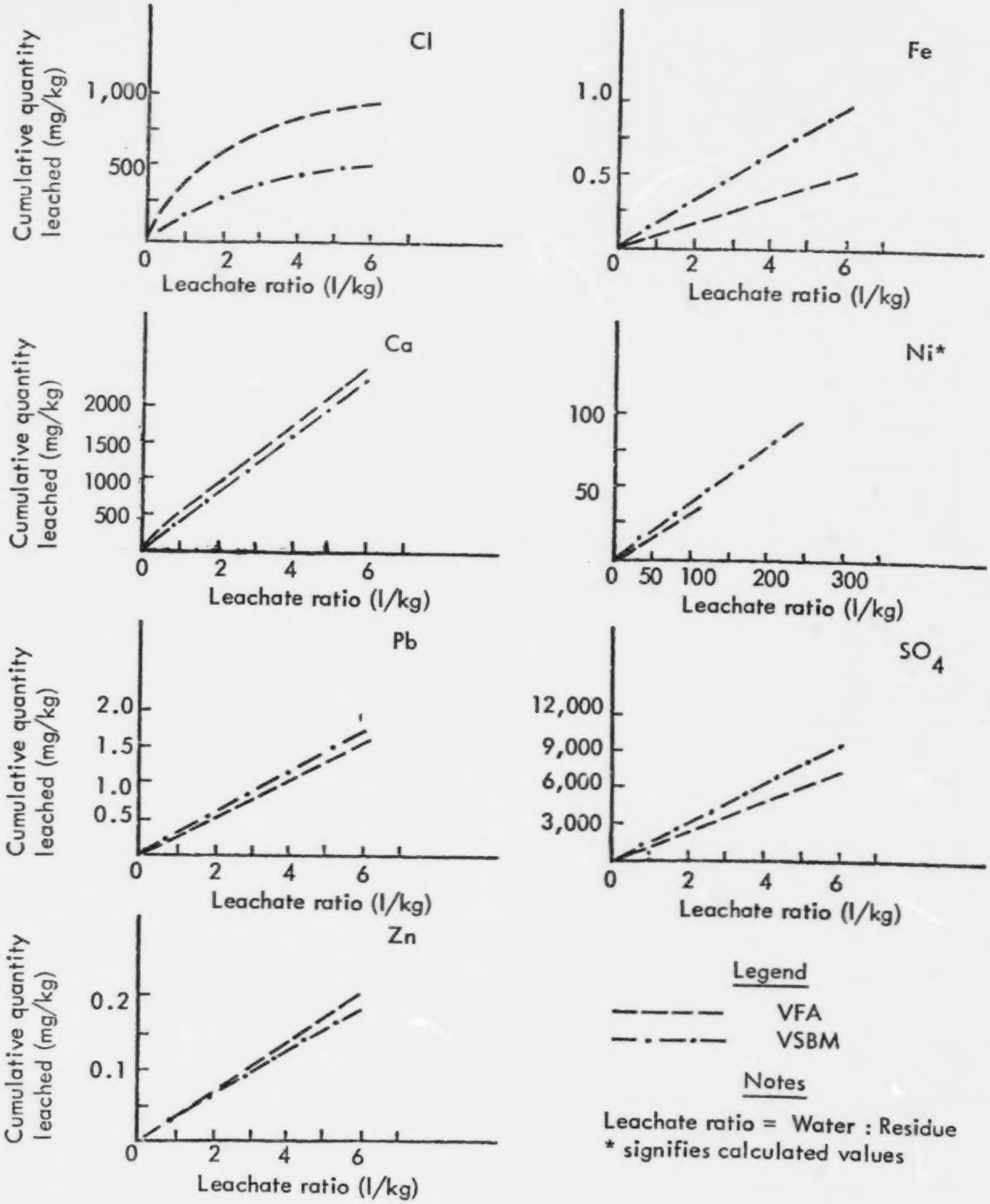
The acid neutralization capacities are found in Table 25. The values ranged from 2.6 equivalents of 1.0 N hydrochloric acid per kg for VSBM to 78.1 for the EFA. These results were useful in indicating the potential for using fluidized-bed residues to condition acidic soils.

The cation exchange capacities of the residues and the stratal materials are shown in Table 26. EFA had the greatest exchange capacity at 13.6 ml per 100 g of residue. NJSBM and ESBM had exchange capacities of 1.9 mg per 100 ml, while VFA and VSBM were found to have 2.4 mg per 100 ml. NJFA was rated at 0.5 mg per 100 ml. The cation exchange capacity for the stratal materials tested ranged from 0.6 for limestone to 26.6 mg per 100 ml for decomposed granite.



Notes
Leachate ratio = Water : Residue
* signifies calculated values

Figure 5 . Leaching characteristics of NJFA and NJSBM.



Notes

Leachate ratio = Water : Residue
* signifies calculated values

Figure 6. Leaching characteristics of VFA and VSBM.

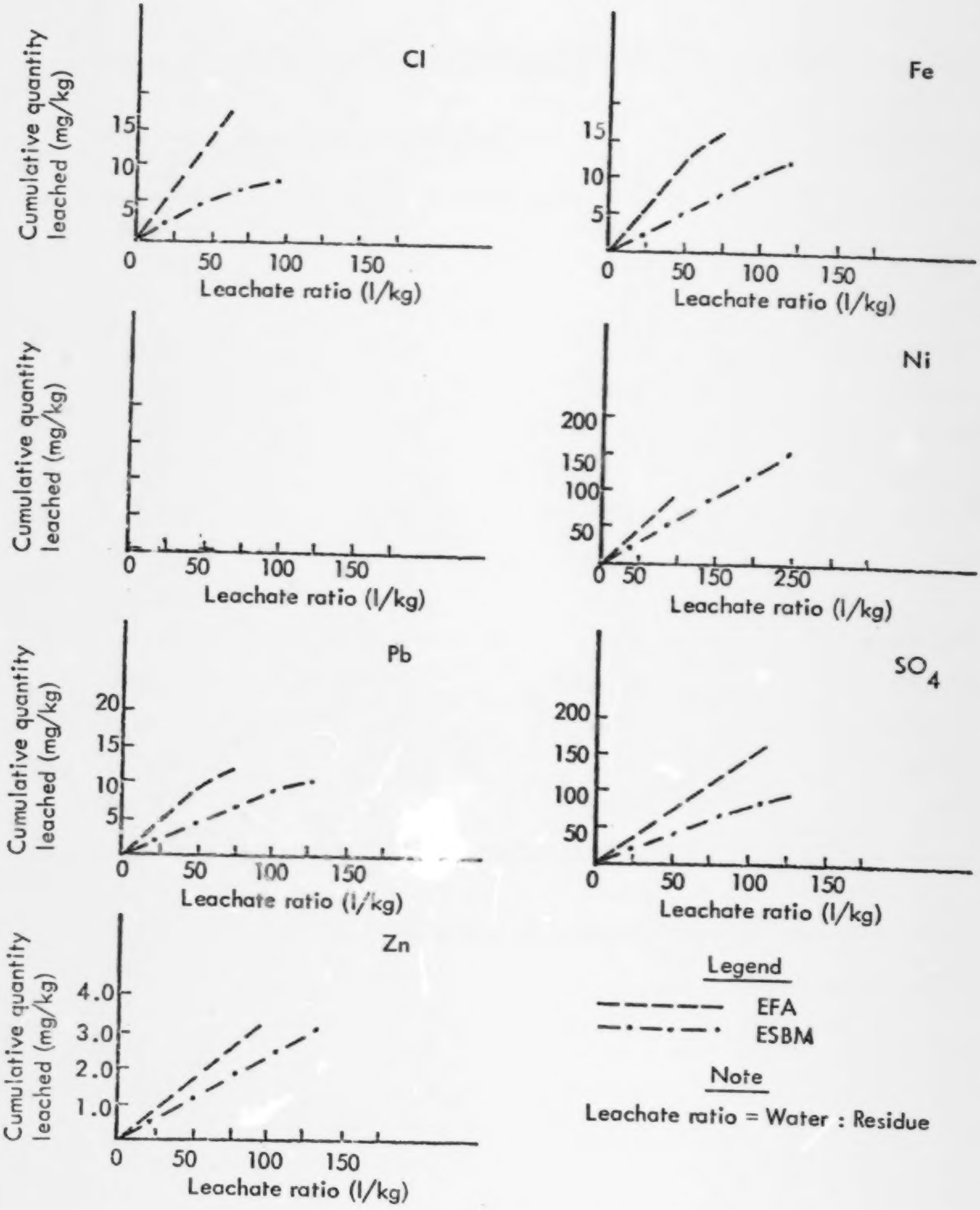


Figure 7. Leaching characteristics of EFA and ESBM.

TABLE 18. LABORATORY LEACHING[a] TESTS: LIMESTONE

Constituent[b]	Total Volume of Leachate (ml)		
	250	500	750
pH	9.5	8.8	8.9
Chloride	<5	<5	<5
Nitrate	<0.1	<0.1	--
Sulfate	10.0	19.0	6.0
Arsenic	<0.001	1.6	1.6
Boron	--	--	0.7
Cadmium	0.01	--	0.01
Calcium	<0.05	<0.05	<0.05
Iron	<0.05	<0.05	<0.05
Lead	0.6	<0.01	<0.01
Magnesium	<0.01	<0.01	<0.01
Mercury	<0.0002	<0.0002	<0.0002
Potassium	3.0	<0.1	1.0
Sodium	74.0	68.0	63.0
Zinc	<0.01	<0.01	<0.01

[a] Water percolated through the bench scale residue sample.

[b] Mg/l except for pH.

TABLE 19. LABORATORY LEACHING[a] TESTS: DOLOMITE

Constituent[b]	Total Volume of Leachate (ml)		
	250	500	750
pH	9.6	8.8	9.2
Chloride	< 5	< 5	< 5
Nitrate	< 0.1	< 0.1	< 0.1
Sulfate	9.0	3.0	< 1.0
Arsenic	0.8	0.8	0.8
Boron	--	--	0.6
Cadmium	< 0.01	--	ND
Calcium	2.2	0.1	< 0.05
Iron	< 0.05	< 0.05	< 0.05
Lead	0.1	< 0.01	< 0.01
Magnesium	< 0.01	< 0.01	< 0.01
Mercury	< 0.0002	< 0.0002	< 0.0002
Potassium	8.0	< 0.1	< 0.1
Sodium	103.0	61.0	60.0
Zinc	< 0.01	< 0.01	< 0.01

[a] Water percolated through the bench scale residue sample.

[b] Mg/l except for pH.

TABLE 20. LABORATORY LEACHING TESTS[a]. BITUMINOUS COAL

Constituent[b]	Total Volume of Leachate (ml)		
	250	500	750
pH	9.0	8.8	8.8
Chloride	< 5	< 5	< 5
Nitrate	< 0.1	< 0.1	--
Sulfate	232.0	42.0	10.0
Arsenic	2.5	5.0	2.5
Boron	--	--	< 0.1
Cadmium	< 0.01	--	< 0.01
Calcium	3.6	0.3	0.9
Iron	< 0.05	< 0.05	< 0.05
Lead	< 0.01	< 0.01	< 0.01
Magnesium	< 0.01	< 0.01	< 0.01
Mercury	< 0.0002	< 0.0002	< 0.0002
Potassium	4.0	< 0.1	1.0
Sodium	80.0	56.0	64.0
Zinc	< 0.01	< 0.01	< 0.01

[a] Water percolated through the bench scale residue sample.

[b] Mg/l except for pH.

TABLE 21. LABORATORY LEACHING[a] TESTS: CLAYSTONE

Constituent[b]	Total Volume of Leachate (ml)		
	250	500	750
pH	9.2	8.8	9.0
Chloride	65	< 5	< 5
Nitrate	< 0.1	< 0.1	--
Sulfate	141.0	9.0	2.5
Arsenic	0.8	1.6	1.6
Boron	--	< 0.1	< 0.1
Cadmium	< 0.01	--	< 0.01
Calcium	0.4	< 0.05	< 0.05
Iron	0.1	< 0.05	< 0.05
Lead	< 0.01	< 0.01	< 0.01
Magnesium	0.1	< 0.01	< 0.01
Mercury	< 0.0002	< 0.0002	< 0.0002
Potassium	< 0.1	< 0.10	< 0.1
Sodium	161.0	97.0	71.0
Zinc	< 0.01	< 0.01	< 0.01

[a] Water percolated through the bench scale residue sample.

[b] Mg/l except for pH.

TABLE 22. LABORATORY LEACHING[a] TESTS: #60 SILICA SAND

Constituent[b]	Total Volume of Leachate (ml)		
	250	500	750
pH	9.0	8.8	9.1
Chloride	75.0	< 5	< 5
Nitrate	< 0.1	< 0.1	--
Sulfate	123.0	30.0	5.0
Arsenic	< 0.001	< 0.001	1.6
Boron	--	--	< 0.1
Cadmium	0.01	--	< 0.01
Calcium	< 0.05	< 0.05	< 0.05
Iron	< 0.05	< 0.05	< 0.05
Lead	< 0.01	< 0.01	< 0.01
Magnesium	< 0.01	< 0.01	0.7
Mercury	< 0.0002	< 0.0002	< 0.0002
Potassium	3.0	< 0.1	2.0
Sodium	168.0	77.0	70.0
Zinc	< 0.01	< 0.01	< 0.01

[a] Water percolated through the bench scale residue sample.

[b] Mg/l except for pH.

TABLE 23. LABORATORY LEACHING[a] TESTS: #16 SILICA SAND

Constituent[b]	Total Volume of Leachate (ml)		
	250	500	750
pH	10.0	8.8	8.8
Chloride	9.0	< 5	<5
Nitrate	<0.1	< 0.1	--
Sulfate	103.0	12.0	7.0
Arsenic	0.8	< 0.001	< 0.001
Boron	--	--	< 0.10
Cadmium	<0.01	--	< 0.01
Calcium	3.7	< 0.05	< 0.05
Iron	<0.05	< 0.05	< 0.05
Lead	0.2	< 0.01	< 0.01
Magnesium	< 0.01	0.03	< 0.01
Mercury	< 0.0002	< 0.0002	< 0.0002
Potassium	50.0	< 0.1	< 0.1
Sodium	245.0	68.0	62.0
Zinc	< 0.01	< 0.01	< 0.01

[a] Water percolated through the bench scale residue sample.

[b] Mg/l except for pH.

TABLE 24. LABORATORY LEACHING TESTS: GRANITE BEDROCK[a]

Constituent[b]	Total Volume of Leachate (ml)		
	250	500	750
pH	9.2	8.8	8.9
Chloride	< 5	< 5	< 5
Nitrate	< 0.1	< 0.1	--
Sulfate	34.0	10.0	2.5
Arsenic	2.5	< 0.001	0.8
Boron	--	--	< 0.1
Cadmium	< 0.01	--	ND
Calcium	1.0	< 0.05	< 0.05
Iron	< 0.05	< 0.05	< 0.05
Lead	< 0.01	< 0.01	< 0.01
Magnesium	< 0.01	< 0.01	< 0.01
Mercury	--	< 0.0002	< 0.0002
Potassium	< 0.1	< 0.1	< 0.1
Sodium	72.0	60.0	64.0
Zinc	< 0.01	< 0.01	< 0.01

[a] Water percolated through the bench scale residue sample.

[b] Mg/l except for pH.

TABLE 25 . RESIDUE ACID NEUTRALIZATION CAPACITY

Residue Type	Neutralization Capacity (equivalent of 1 N HCl/kg residue)
NJFA	17.5
NJSBM	26.0
VFA	8.8
VSBM	2.6
EFA	78.1
ESBM	35.5

TABLE 26 . RESIDUE AND COLUMN MATERIAL CATION EXCHANGE CAPACITY

Material[a]	CEC meq/100g residue
EFA	13.6
ESBM	1.9
VFA	2.4
VSBM	2.4
NJFA	0.5
NJSBM	1.9
Limestone	0.6
Dolomite	1.9
Bituminous coal	2.7
Claystone/sand, 4:1	7.2
Decomposed granite	26.6
#16 Silica sand	1.4
#60 Silica sand	2.8

[a] Residues were slaked before determining CEC.

Slaking results for the residues are shown in Figures 8 and 9. The slaking temperature for NJSBM reached a maximum of 220° C after 1,000 sec. The temperature of the VFA, VSBM, and EFA also increased with the addition of 3.8 l of water to 13.6 kg dry residue. NJFA did not show any signs of exothermic reaction with water, probably due to a lower content of lime. In fact, VFA probably contained less calcium oxide than VSBM since the fly ash rose to a maximum of 35° C compared to the spent bed residue which reached a temperature of 100° C.

Physical Properties

The results from the hydrometer and the sieve analyses were plotted together, and are presented in Figures 10 and 11. Additional sieve analyses for the strata material are also shown in Figures 12 to 14.

The fluidized-bed fly ash particle sizes were fine (similar to a type of sandy silt) and the composition was unchanged by slaking. The spent bed material particle sizes, as received, were similar to sand and became even finer after slaking. Oil gasification residue particle analyses fell within a narrow band corresponding to a typical sand with fines. The exception was unslaked Esso spent bed materials whose paricle size distribution corresponded to a typical sand.

The specific gravity, moisture content, degree of saturation, loose dry density,and the water-holding capacity determined for the fluidized bed residues are listed in Table 27.

The specific gravity values for Exxon and PER fly ashes (2.6 - 2.8) were in the range for normal soils. Esso fly ash specific gravity of 2.02 was less than that for normal soils. The spent bed residues were partially dissolved,thus, their specific gravity was not determined. The residues "as received" had no moisture content, and as a result, the degree of saturation was zero for all the residues. The addition of water to the dry residues changed the dry densities of all the residues tested except VFA. The dry density of the EFA and ESBM decreased by 37 and 49 percent dry weight after slaking. NJSBM, on the other hand, increased from 0.73 g/cc before slaking to 1.08 g/cc after slaking, a 48 percent increase. The ability of dry slaked residues to hold moisture, termed their water-holding capacity, ranged between 0.44 and 0.98 grams of water per gram of dry sample.

The results of the permeability tests for the residues and stratal materials are shown in Table 28. The hydraulic conductivities ranged from 6.8×10^{-4} to 3.7×10^{-2} cm/sec for the residues; and, for the stratal materials, the permeability values ranged between 1.6×10^{-4} for sandy loam to 8.2×10^{-2} cm/sec for gravel.

The results of the physical and chemical characterization of the fluidized-bed residues and the stratum materials were the basis for planning the construction of the larger pilot test columns (see Chapter 6) which more closely simulated specific disposal environments.

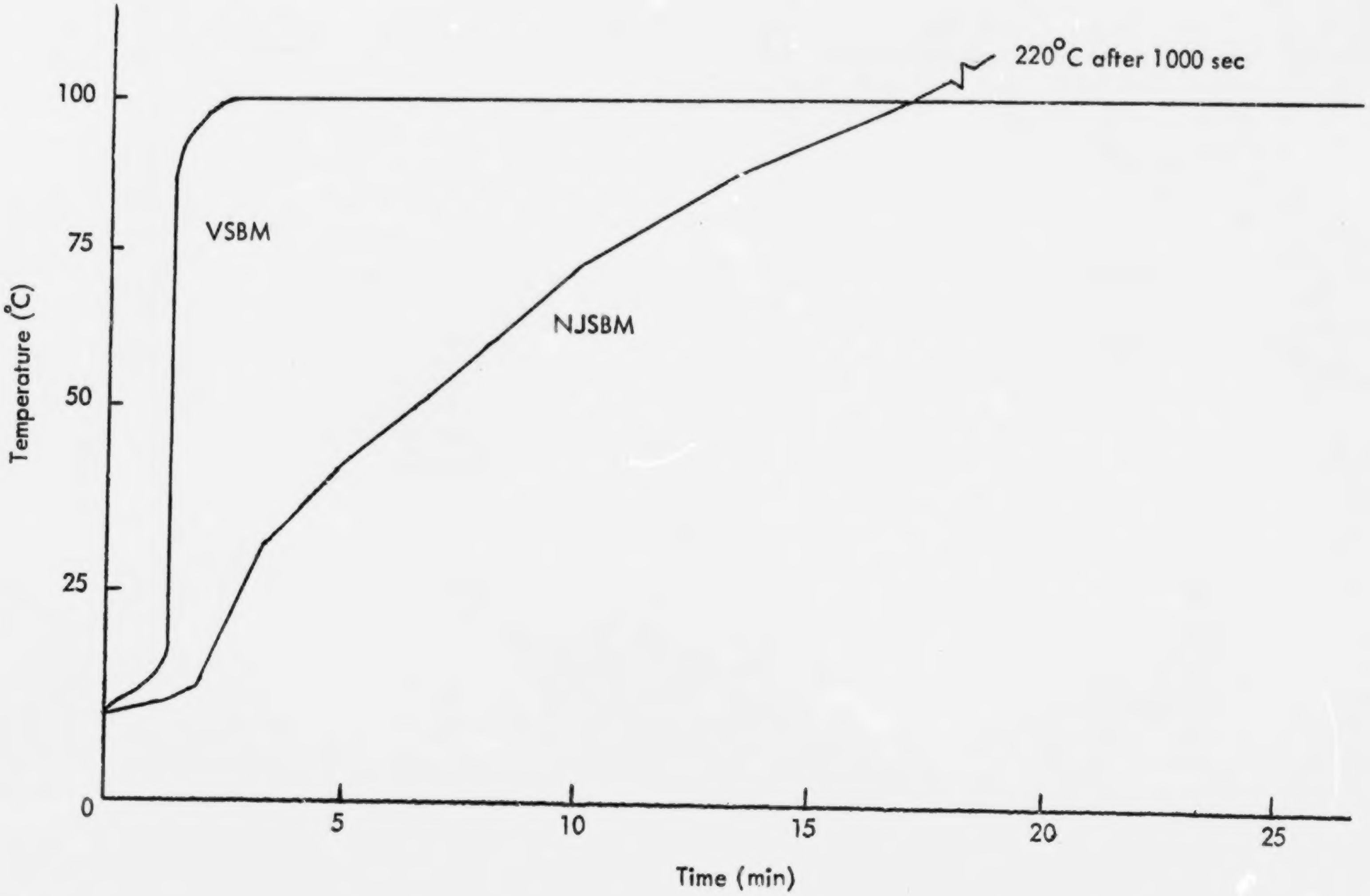


Figure 8. Temperature change from water addition to dry residues.

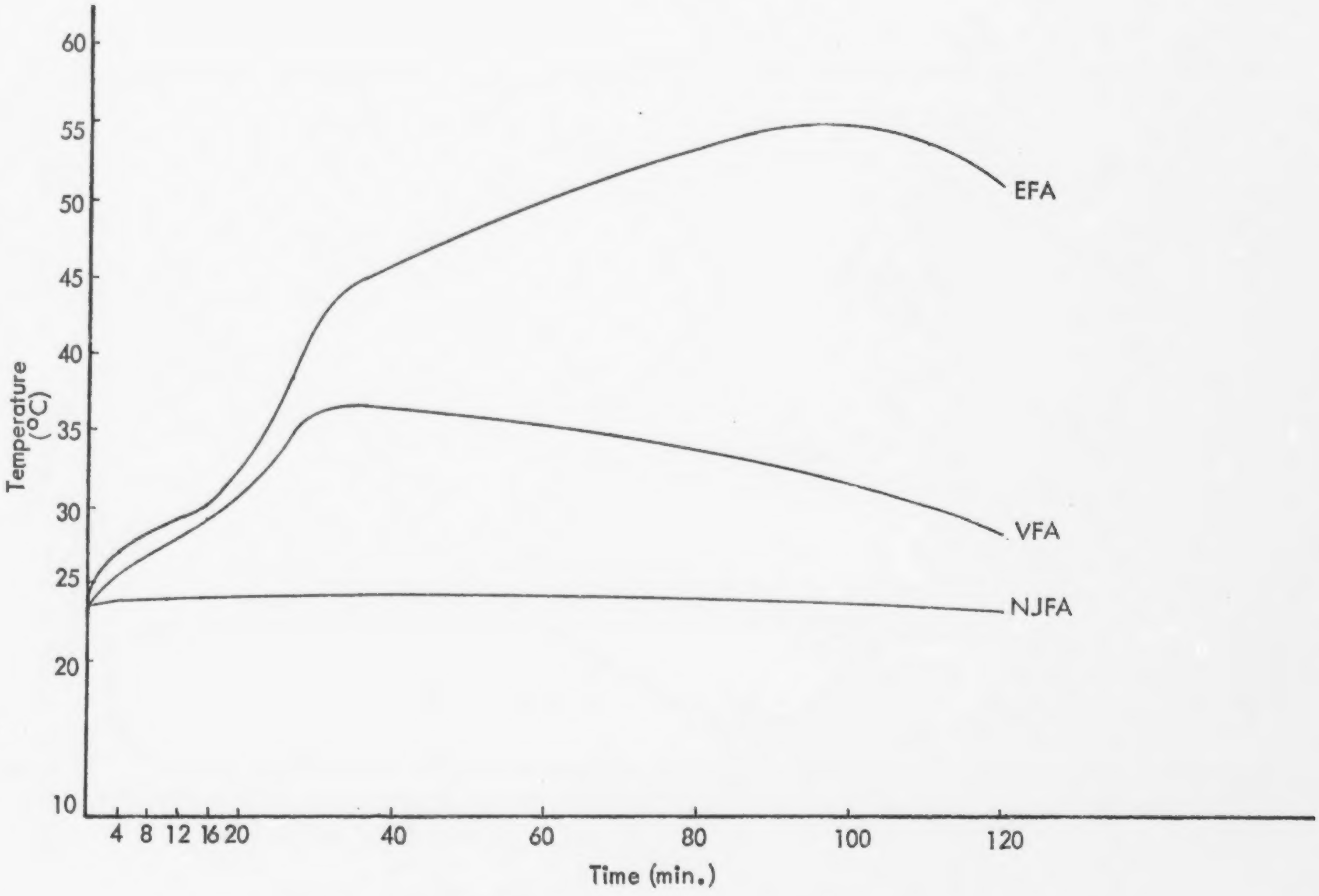


Figure 9. Temperature change from water addition to dry residues.

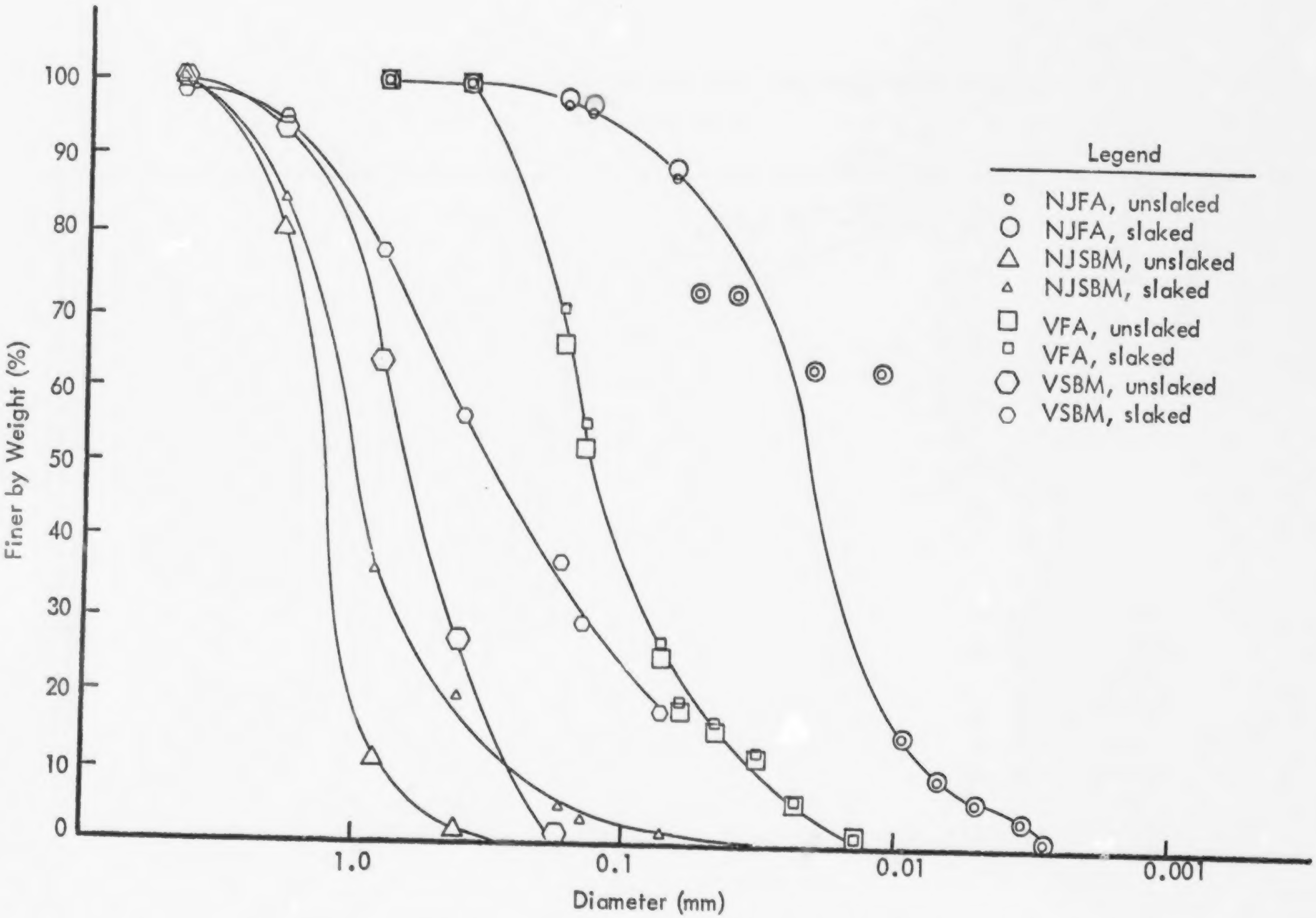


Figure 10. Particle size analyses: coal combustion residues.

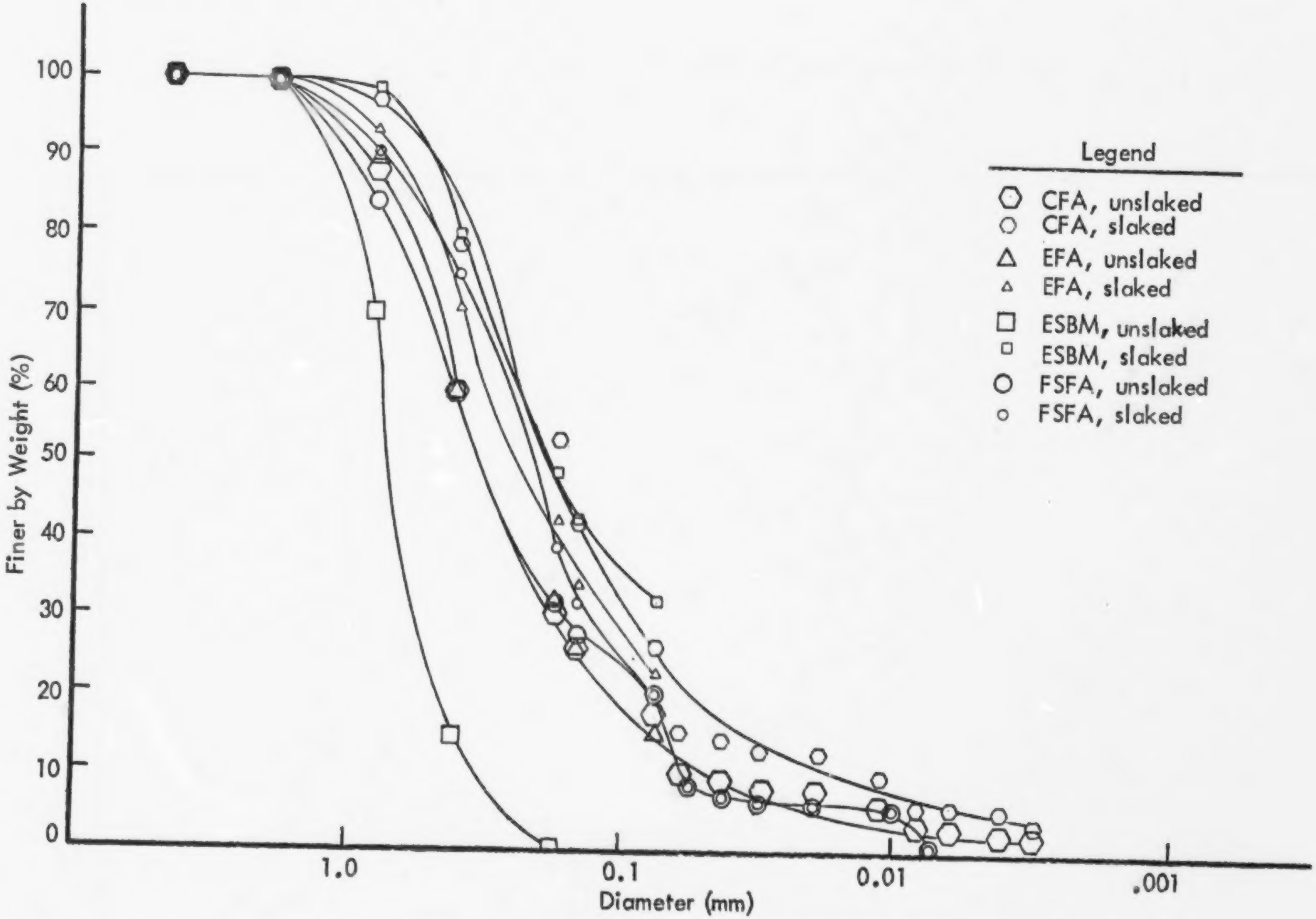


Figure 11. Particle size analyses : oil gasification residues.

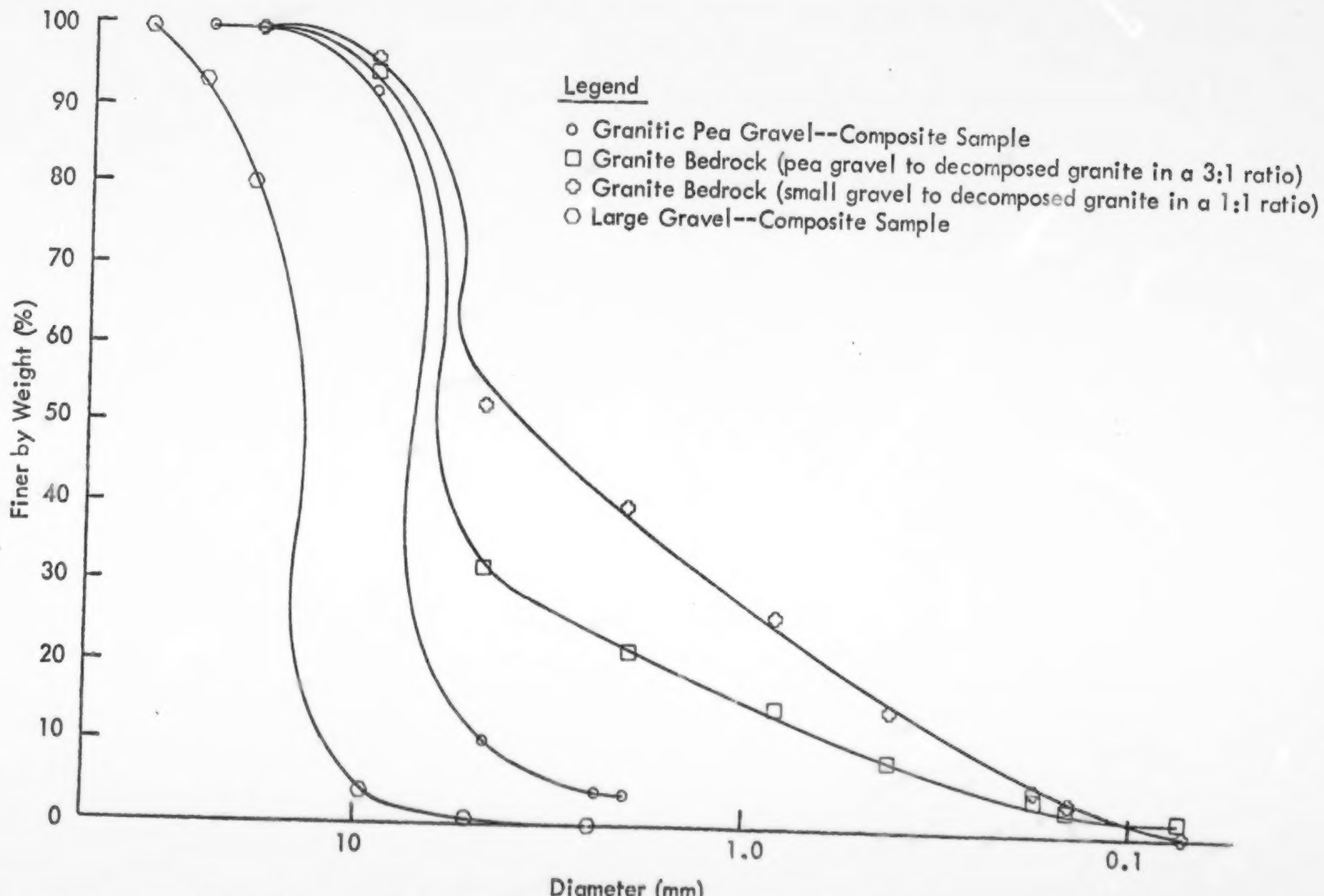


Figure 12. Particle size analysis: pea gravel, granite bedrock, and large gravel.

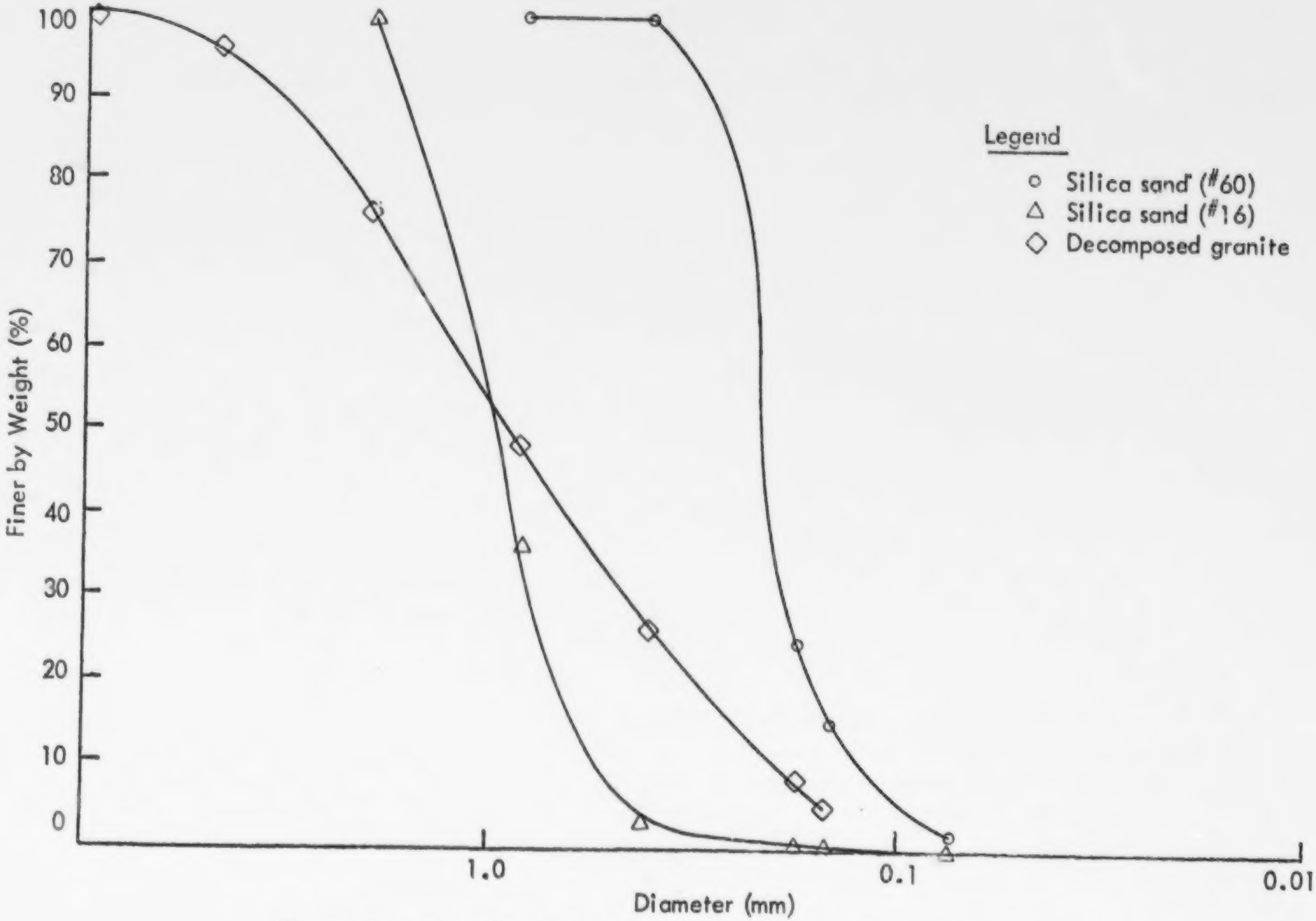


Figure 13. Particle size analysis: silica sand and decomposed granite.

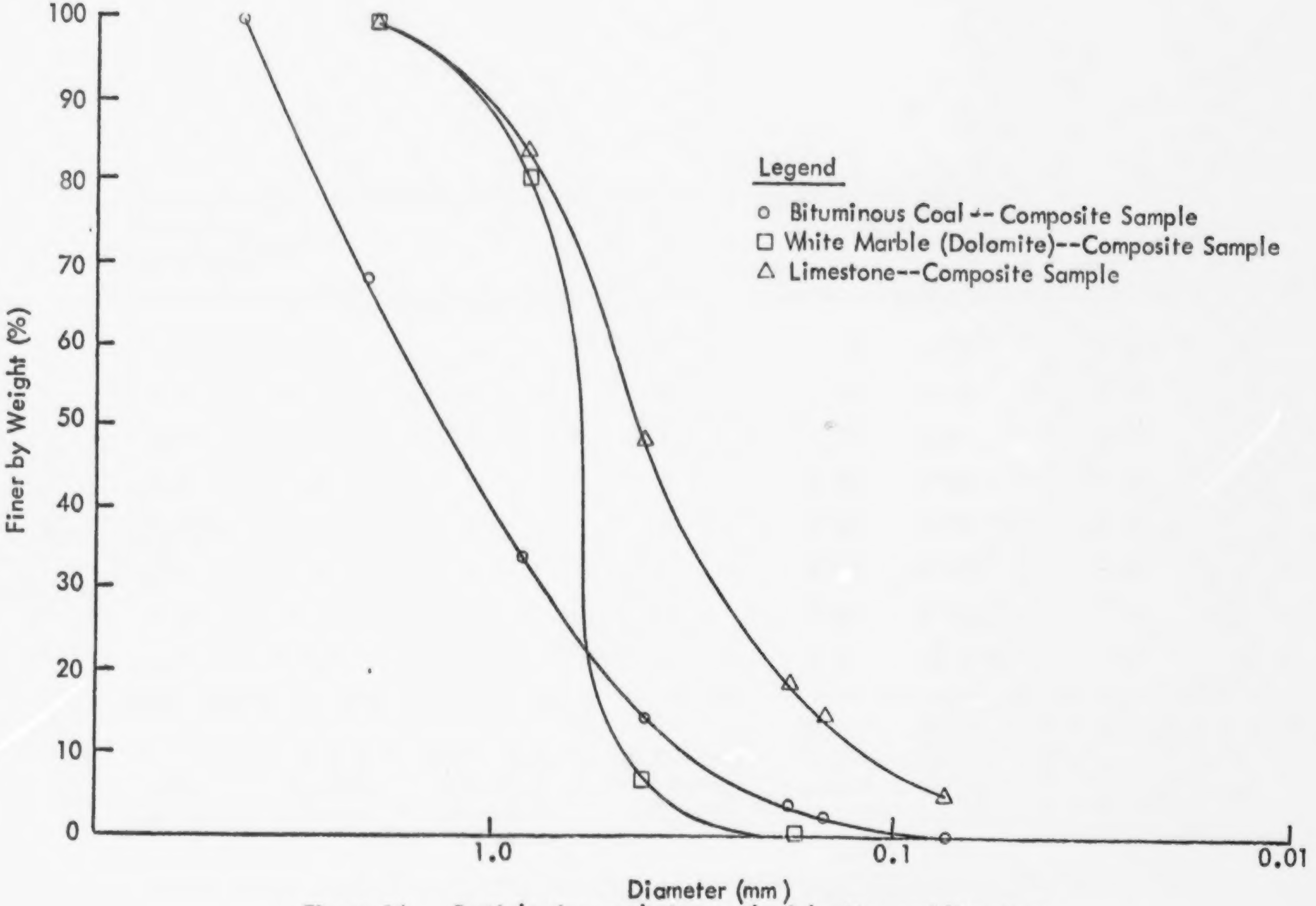


Figure 14. Particle size analysis: coal, dolomite, and limestone.

TABLE 27. RESIDUE PHYSICAL PROPERTIES

Residue Type	Specific Gravity[a] (g/cc)	Moisture Content[b] (% dry wt.)	Degree of Saturation[b] (% dry wt.)	Dry Density		Water-holding Capacity $\left(\frac{\text{g } H_2O}{\text{g Residue}}\right)$
				Before Slaking[b] (g/cc)	After Slaking (g/cc)	
VFA	2.65	0	0	0.76	0.76	0.66
VSBM	c	0	0	0.92	0.97	0.50
NJFA	2.71	0	0	0.74	0.65	0.74
NJSBM	c	0	0	0.73	1.08	0.44
EFA	2.02	0	0	1.46	0.88	0.70
ESBM	c	0	0	1.36	0.67	0.98
CFA	2.72	0	0	1.09	0.78	0.76
FSFA	3.11	0	0	1.18	0.76	0.78

[a] After slaking.

[b] As received.

[c] Not obtainable, as some portion of the material in question enters into solution.

TABLE 28. PERMEABILITY OF RESIDUES AND COLUMN MATERIALS

Description	Hydraulic Conductivity K (cm/sec)
Residue	
PER Virginia fly ash	1.9×10^{-3}
PER Virginia spent bed material (slaked)	1.9×10^{-3}
Exxon New Jersey fly ash	6.4×10^{-4}
Exxon New Jersey spent bed material (slaked)	3.7×10^{-2}
Esso, England fly ash (slaked)	1.6×10^{-3}
Esso, England spent bed material (slaked)	6.8×10^{-4}
Column Material	
Limestone (granular)	1.0×10^{-2}
Dolomite (granular)	5.9×10^{-2}
Bituminous Coal (granular)	6.1×10^{-2}
Sanitary landfill	7.0×10^{-2}
Claystone (4:1, #60 sand to clay)*	1.64×10^{-3}
Sandstone (#60 sand)	3.2×10^{-2}
Sandstone (#16 sand)	7.4×10^{-2}
Clayey loam (3:1 #60 sand to soil)*	1.1×10^{-3}
Silty loam (3:1 #60 sand to soil) *	1.0×10^{-2}
Sandy loam	1.6×10^{-4}
Granite bedrock (3:1 p-gravel to decomposed granite)*	5.2×10^{-3}
Gravel	8.2×10^{-2}

*By weight

CHAPTER 7

PILOT COLUMN STUDIES OF RESIDUE DISPOSAL

Purpose

The primary purpose of this study was to evaluate the possible impacts of residue disposal on different environments. The first step in this evaluation was to simulate likely disposal locations on a pilot scale. This was done to allow testing under defined conditions, and to control the physical and climatic variables which would otherwise affect the behavior of the residues in natural environments. In the following section, the construction and evaluation of the simulated disposal environments are presented.

Simulated Sedimentary Environmental Columns

Pilot test columns with simulated natural environments were constructed in 20.3 cm ID PVC pipe. The various environments, chosen to simulate potential natural disposal sites, were limestone and dolomite quarries, sanitary landfill, coal mine, ocean, and sandy, clayey, and silty loam soils. A description of the columns constructed are presented in Table 29, by number code, environment, and residue type tested. For each simulated disposal environment, stratigraphic configurations were developed using the literature search data and scaled to fit within the column's dimensions. Typical actual environments and the stratigraphic configurations of the test columns are described in the following paragraphs (see Figure 15, legend for test column disposal environments).

Limestone and Dolomite Quarries

Actual Location. An abandoned limestone quarry might contain 20 to 40 percent limestone; this remaining unquarried limestone would normally be left in place because it was of poor quality, or not economically feasible to mine. The sedimentary sequence of the quarry would probably consist of a series of limestone, shale, and sandstone beds. This type of strata occurs with varying percentages relative to each other. No "typical" strata below a limestone or dolomite quarry exists. It might be all sandstone, shale, or a combination of any of the latter three types of strata. For this reason, an arbitrary "known" sequence was selected from a real world quarry (see Table 30).

Test Column. The test columns represented a configuration in which residues would be deposited in an abondoned quarry pit and underlain by the thickness of strata shown in Table 30 (assuming a depth to the groundwater table of about 30 m). In this 30 m section, below the residues, there would be 14.2 m of limestone, 1.04 m of claystone, and 14.2 m of sandstone. Figures 16 and 17 show the actual composition of the simulated limestone and dolomite quarries. Relatively impermeable materials, such as claystone, were mixed with standard Ottawa sand to provide greater permeability, thus resulting in reduced scale coefficients. Obviously, standard claystone is so impervious that without the increase in permeability provided by the sand mixture, there would have been no significant column leachate. In nature, however, there is slow water movement over large areas

TABLE 29. COLUMN AND RESIDUE IDENTIFICATION

Column No.	Environment	Operating Conditions of Test Run[a]								
		Residue	No.	Date	Average Temperature (°C)	Fuel Type	Excess Air (%)	Bed Sorbent	Ca/S mfr	Average Flue SO_2 (ppm)
1	Ocean	VSBM	NA[b]	NA	843	Sewickley coal	18	Germany Valley limestone	Variable	Variable
2	Limestone	NJSBM	19.7	8-28-75	905-910	Champion coal (eastern)	9.4	Grove limestone	2.5	360
3	Limestone	VSBM	NA							
4	Limestone	NJFA	19.7	8-28-75						
5	Limestone	VFA								
6	Dolomite	VSBM								
7	Dolomite	NJSBM	19.7	8-28-75						
8	Dolomite	NJFA	19.7	8-28-75						
9	Dolomite	VFA								
10	Landfill	VFA	NA	NA	843	Sewickley coal	18	Germany Valley limestone	Variable	Variable
11	Landfill	VSBM								
12	Landfill	NJFA	19.7	8-28-75						
13	Landfill	NJSBM	19.7	8-28-75						
14	Coal mine	VSBM								
15	Coal mine	NJSBM	19.7	8-28-75						
16	Coal mine	NJFA	19.7	8-28-75						
17	Coal mine	VFA								
18	Ocean	NJFA	19.7	8-28-75						
19	Ocean	NJSBM	19.7	8-28-75						
20	Ocean	VFA								

(continued)

TABLE 29 (Cont.)

Column No.	Environment	Operating Conditions of Test Run[a] Residue	No.	Date	Average Temperature (°C)	Fuel Type	Excess Air (%)	Bed Sorbent	Ca/S mfr	Average Flue SO_2 (ppm)
21	Ocean	EFA	NA	11-10-75	890	#6 oil	5-10	BCR 1359 lime	1	200
22	Ocean	ESBM								
23	Limestone	EFA								
24	Limestone	ESBM								
25	Dolomite	EFA								
26	Dolomite	ESBM								
27	Landfill	EFA								
28	Landfill	ESBM								
29	Coal mine	EFA								
30	Coal mine	ESBM								
31	Sandy loam	EFA								
32	Sandy loam	ESBM								
33	Clay loam	EFA								
34	Clay loam	ESBM								
35	Silty loam	EFA								
36	Silty loam	ESBM								

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[a] Operating conditions at the pilot plant test site.

[b] NA - Not available.

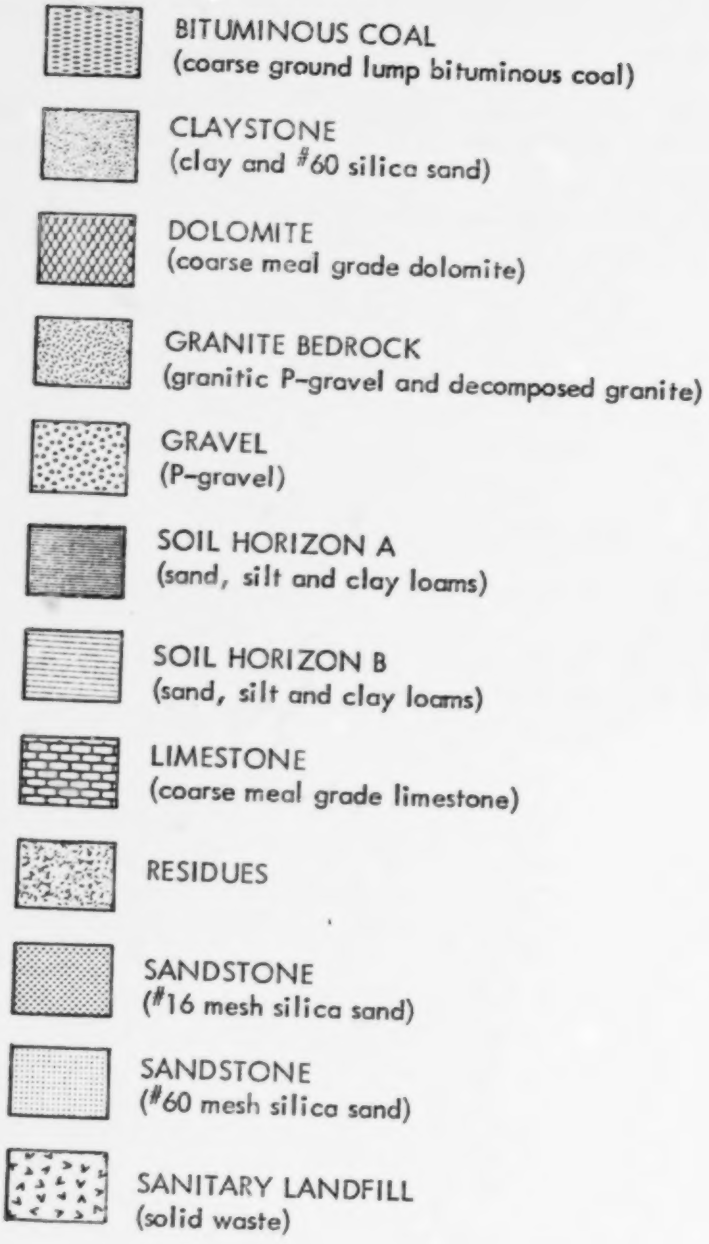

BITUMINOUS COAL
(coarse ground lump bituminous coal)
CLAYSTONE
(clay and #60 silica sand)
DOLOMITE
(coarse meal grade dolomite)
GRANITE BEDROCK
(granitic P-gravel and decomposed granite)
GRAVEL
(P-gravel)
SOIL HORIZON A
(sand, silt and clay loams)
SOIL HORIZON B
(sand, silt and clay loams)
LIMESTONE
(coarse meal grade limestone)
RESIDUES
SANDSTONE
(#16 mesh silica sand)
SANDSTONE
(#60 mesh silica sand)
SANITARY LANDFILL
(solid waste)

Figure 15 . Legend for test column disposal environments.

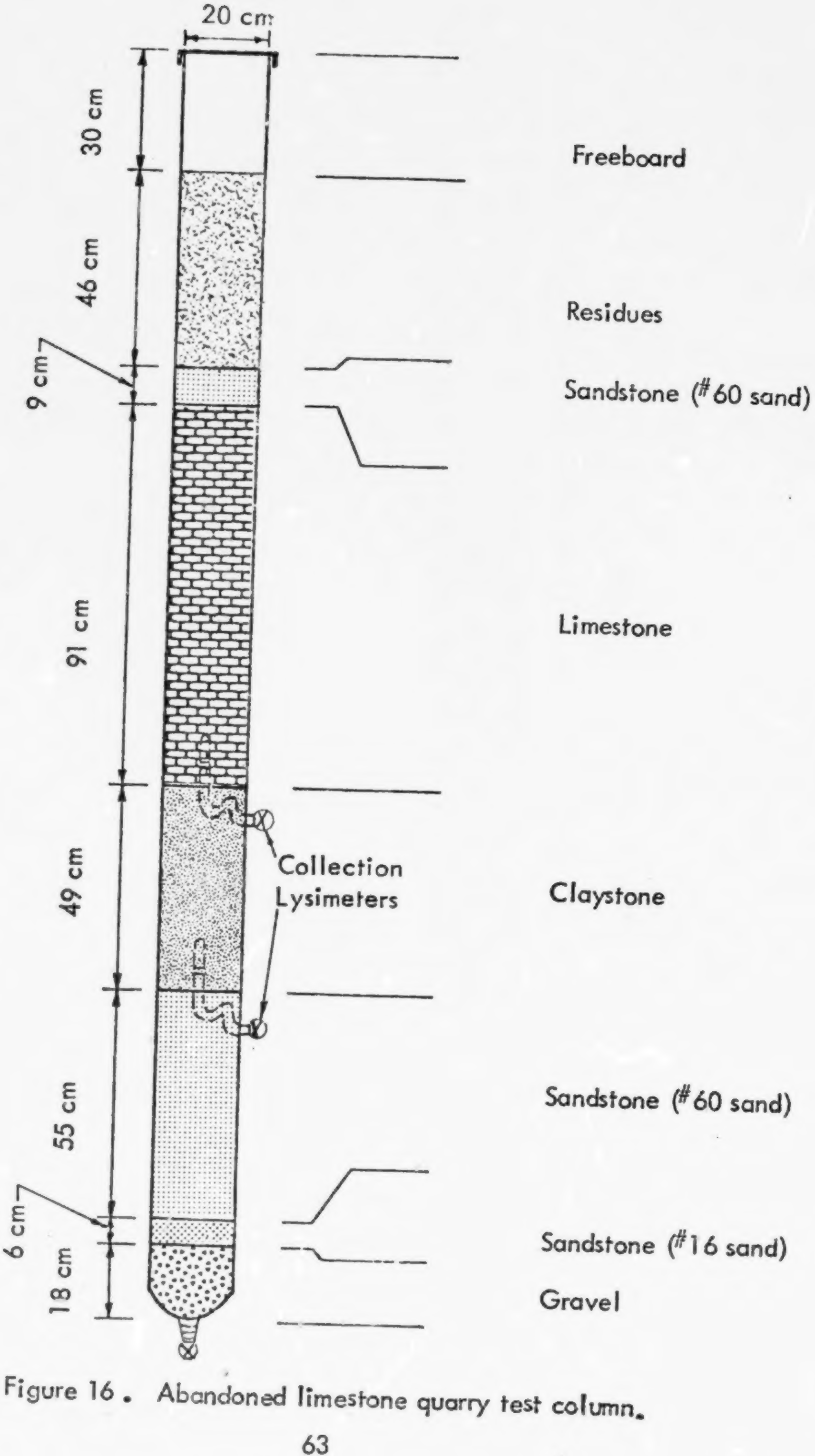
TABLE 30. REPRESENTATIVE THICKNESSES OF LIMESTONE & DOLOMITE SIMULATION TEST COLUMNS

Limestone Quarry			Dolomite Quarry		
Material	Representative Stratum Thicknesses (m)*	Scale (a) Coefficient	Material	Representative Stratum Thicknesses (m)	Scale (a) Coefficient
Limestone	14.2	15.7	Dolomite	14.2	15.7
Claystone[b]	1.4	3.9[c]	Claystone	1.4	3.9[c]
Sandstone[d]	14.2	15.7	Sandstone	14.2	15.7

---

[a] Thickness of layer in field to thickness of simulated layer in column.
[b] Excludes add-mixed #60 sand.
[c] As mixed, includes sand with clay in column, for increased permeability.
[d] Includes add-mixed #60 sand from claystone layer.

*Source: 30, 49, 106.



20 cm
30 cm
Freeboard
46 cm
Residues
9 cm
Sandstone (#60 sand)
91 cm
Limestone
49 cm
Collection
Lysimeters
Claystone
55 cm
Sandstone (#60 sand)
6 cm
Sandstone (#16 sand)
18 cm
Gravel

Figure 16. Abandoned limestone quarry test column.

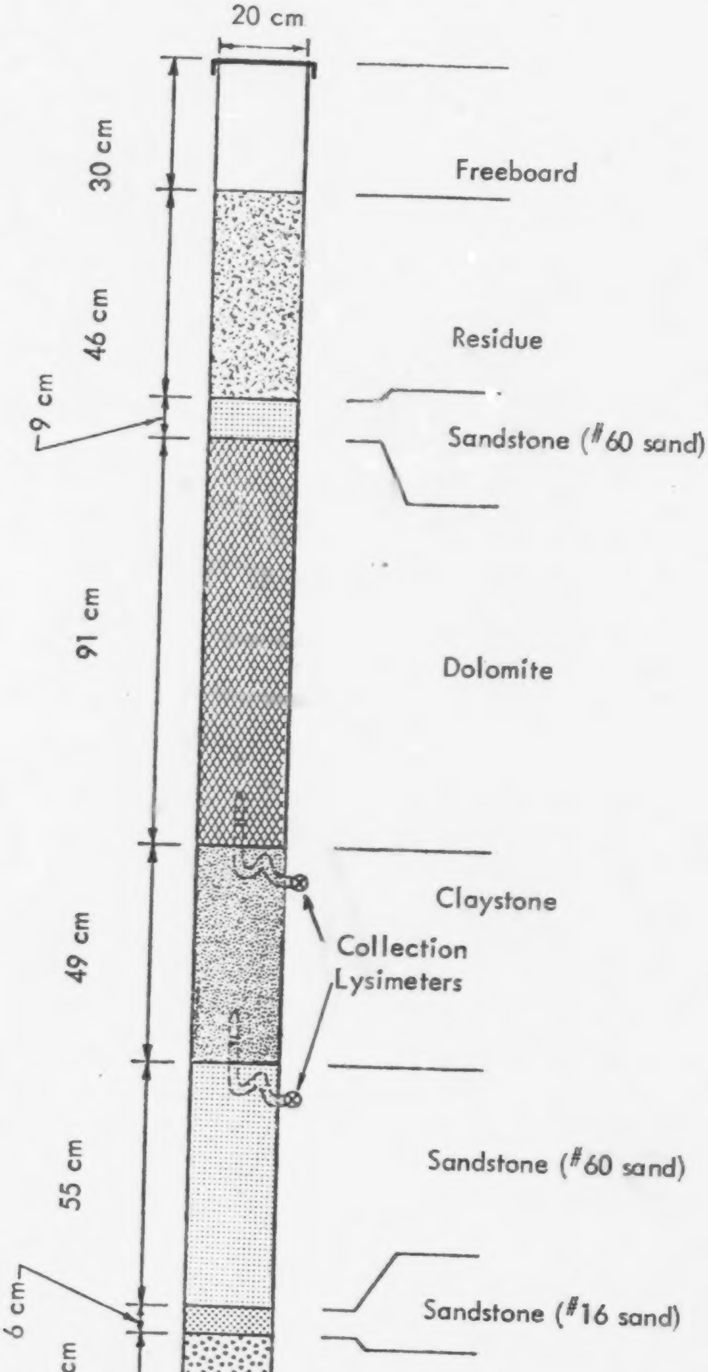

20 cm
30 cm
46 cm
9 cm
91 cm
49 cm
55 cm
6 cm
18 cm
Freeboard
Residue
Sandstone (#60 sand)
Dolomite
Claystone
Collection
Lysimeters
Sandstone (#60 sand)
Sandstone (#16 sand)
Gravel

Figure 17. Simulated sedimentary environment: dolomite quarry test column.

and, hence, considerable leaching through the claystone with time. Therefore, the test columns provided an accelerated type leachate test of what could occur in nature.

Sanitary Landfills

Actual Location. Sanitary landfills are made of diverse materials (a 1 to 10 meter mix of inert residues and organic solid waste, covered with about 15 cm layers of soil), placed in natural ground. A summary of the estimated residential and commercial solid waste generation which may be found in an actual landfill is shown in Table 31. Sanitary landfill was assumed to be 3 m of mixed refuse to 0.15 m of soil fill/lift, i.e., 95 percent solid waste, and 5 percent cover soil. Both residues and refuse landfill can generate pollutants when saturated with water.

Test Column. The sanitary landfill materials used in the test columns were prepared according to the solid waste percentages shown in Table 31. The "as mixed" percentages varied slightly, and are shown in Table 32. Organic solid waste and inert residues were separated for physical testing after preliminary leaching tests. The arbitrarily selected real world landfill environment with a known municipal-type solid waste mixture was next placed in the test columns as shown in Figure 18. Assuming a depth of 30 m below the land surface for the water table, each column represented the conversion factors for the thicknesses of the replicated real world strata materials as shown in Table 33. The scale coefficients of approximately 1:12 were chosen to conveniently replicate the strata in the test column. Again, claystone was admixed with standard Ottawa sand to increase leachate permeability, thus resulting in lower column scale coefficients.

Coal Mine

Actual Location. A typical abandoned coal mine would be underlain by a sequence of shale, sandstone, limestone, and minor coal seams - the dominant sequence being shale (see Figure 19). Residues could be disposed in an abandoned mine underlain by similar strata.

Test Column. The test columns represented the abandoned coal mine environment which was assumed to be underlain by the thicknesses of strata, listed in Table 34, with a 30 m depth to groundwater. The strata configuration in the column was as illustrated in Figure 20.

Ocean Environment

Actual Location. Residue wastes have been disposed into the ocean in many ways including barging and open ocean dumping, piping the wastes in the form of a slurry onto the ocean floor (or into a submarine canyon), or using the residues to fill and create land.

Test Column. The ocean environment test columns replicated a filled-land type of disposal where only the tidal portion of the residue fill would be flushed by sea water for an extended period of time (also waves and land drainage will cause some flushing). The

TABLE 31. ESTIMATED RESIDENTIAL AND COMMERCIAL SOLID WASTE GENERATION BY KIND OF MATERIAL AND PRODUCT SOURCE CATEGORY, 1971

Materials	Product Source Categories "As Generated" Basis (kkg x 10^6)						Material Totals			
							As Generated Basis		As Disposed Basis	
	Newspapers, Books and Magazines	Containers and Packaging	Major Household Appliances	Furniture and Furnishings	Clothing and Footwear	Other Products	kkg x 10^6	Percent	kkg x 10^6	Percent
Paper	9.3	18.5	--	tr[a]	tr	7.6	35.5	31.3	42.9	37.8
Glass	--	10.1	tr	tr	--	0.9	11.0	9.7	11.3	10.0
Metals	--	5.5	1.7	0.1	tr	3.4	10.8	9.5	11.4	10.1
Ferrous	--	4.9	1.5	tr	--	3.2	9.6	8.5	--	--
Aluminum	--	0.5	0.1	tr	--	0.1	0.7	0.6	--	--
Other non-ferrous	--	0.1	0.1	tr	--	0.2	0.4	0.3	--	--
Plastics	tr	2.3	--	0.1	0.2	1.2	3.8	3.4	4.3	3.8
Rubber and leather	--	tr	--	tr	0.5	2.4	3.0	2.6	3.1	2.7
Textiles	tr	tr	--	0.5	0.5	0.6	1.6	1.4	1.8	1.6
Wood	--	1.6	--	2.1	tr	0.5	4.2	3.7	4.2	3.7
Non-food product totals	9.3	38.0	1.9	2.9	1.1	16.6	69.9	61.7	79.1	69.7

(Continued)

TABLE 31 (Cont.)

Materials	Product Source Categories "As Generated" Basis (kkg x 10^6)							Material Totals			
	Newspapers, Books and Magazines	Containers and Packaging	Packaging	Major Household Appliances	Furniture and Furnishings	Clothing and Footwear	Other Products	As Generated Basis		As Disposed Basis	
								kkg x 10^6	Percent	kkg x 10^6	Percent
Food waste								20.0	17.6	16.1	14.2
Product totals								89.9	79.3	95.2	83.9
Yard waste								21.9	19.3	16.5	14.6
Miscellaneous inorganics								1.6	1.4	1.7	1.5
Total waste								113.4	100	113.4	100

---

[a] Tr= Trace

TABLE 32. SANITARY LANDFILL TEST COLUMN-AS MIXED

Materials	Kg	Percent	Description
Paper	8.39	37.7	Shredded newspaper and shredded paper.
Glass	2.27	10.2	Broken bottles, colored and clear.
Metals	2.15	9.7	Cut-up tin cans, cans and cut wire.
Plastics	0.86	3.9	Shredded plastic trash bags and miscellaneous plastics from trash.
Rubber and Leather	0.59	2.7	Cut-up shoes.
Textiles	0.23	1.0	Shredded drapes and rags.
Wood	0.77	3.5	Cut-up wood crates.
Non-Food Product Total	15.26	68.7	
Food Waste	3.18	14.3	Miscellaneous household food waste.
Product Total	18.44	83.0	
Yard Waste	3.40	15.3	Miscellaneous yard waste.
Miscellaneous Inorganics	0.39	1.7	River gravel and silica sand.
Total	22.23	100.0	

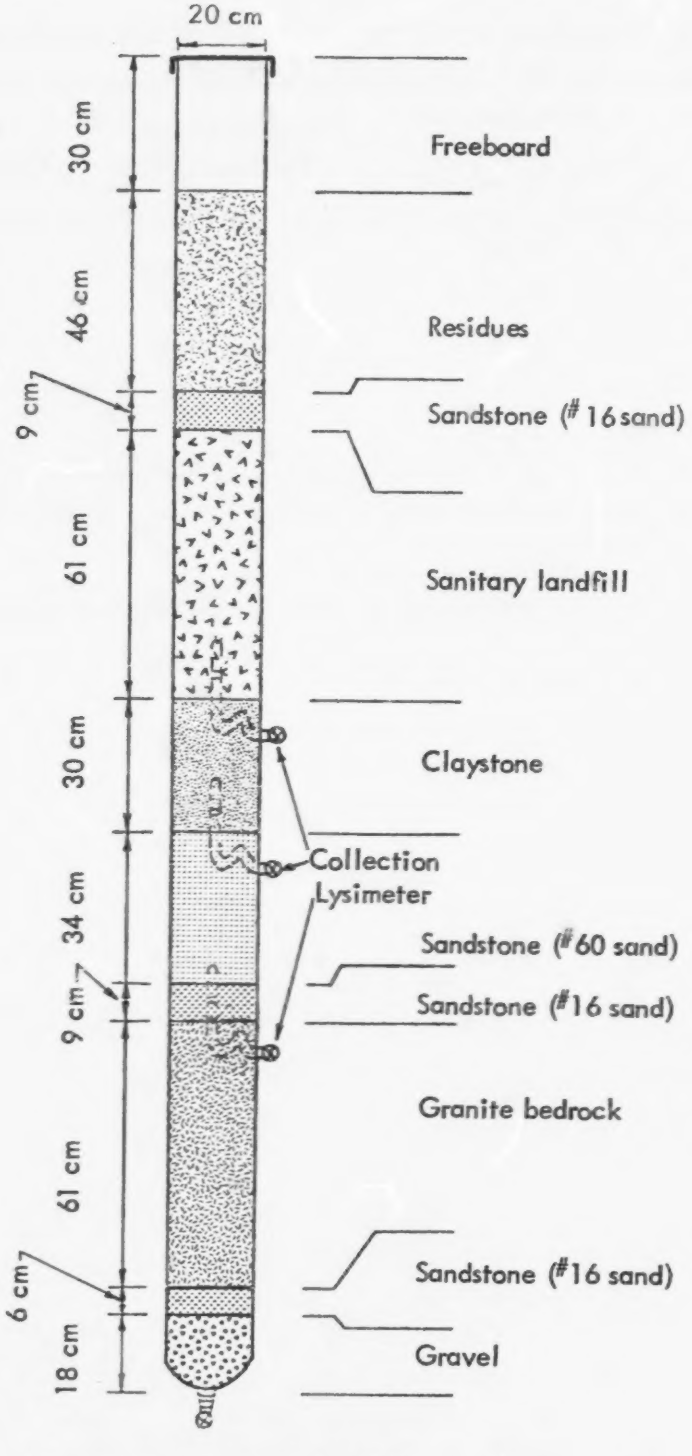

20 cm
30 cm
Freeboard
46 cm
Residues
9 cm
Sandstone (# 16 sand)
61 cm
Sanitary landfill
30 cm
Claystone
Collection Lysimeter
34 cm
Sandstone (#60 sand)
9 cm
Sandstone (#16 sand)
Granite bedrock
61 cm
6 cm
Sandstone (#16 sand)
18 cm
Gravel

Figure 18. Sanitary landfill test column.

TABLE 33. REPRESENTATIVE THICKNESS SANITARY LANDFILL SIMULATED IN TEST COLUMNS

Material	Representative Stratum Thickness (m)	Column Layer Thickness (m)	Scale Coefficient[d]
Residue	5.79	0.46	1:12.6
Solid Waste[a]	7.62	0.61	1:12.5
Claystone[b]	0.91	0.29	1: 3.1
Sandstone[c]	8.54	0.67	1:12.8
Granite Bedrock	7.62	0.61	1:12.5

[a] No decomposition before leaching began in first 20 columns, "fresh" solid waste used.

[b] Excludes admixed #60 sand.

[c] Includes admixed #60 sand from claystone layer.

[d] Thickness of strata in field to thickness of simulated strata in test column (a ratio).

Source: Ralph Stone and Company, Inc. files.

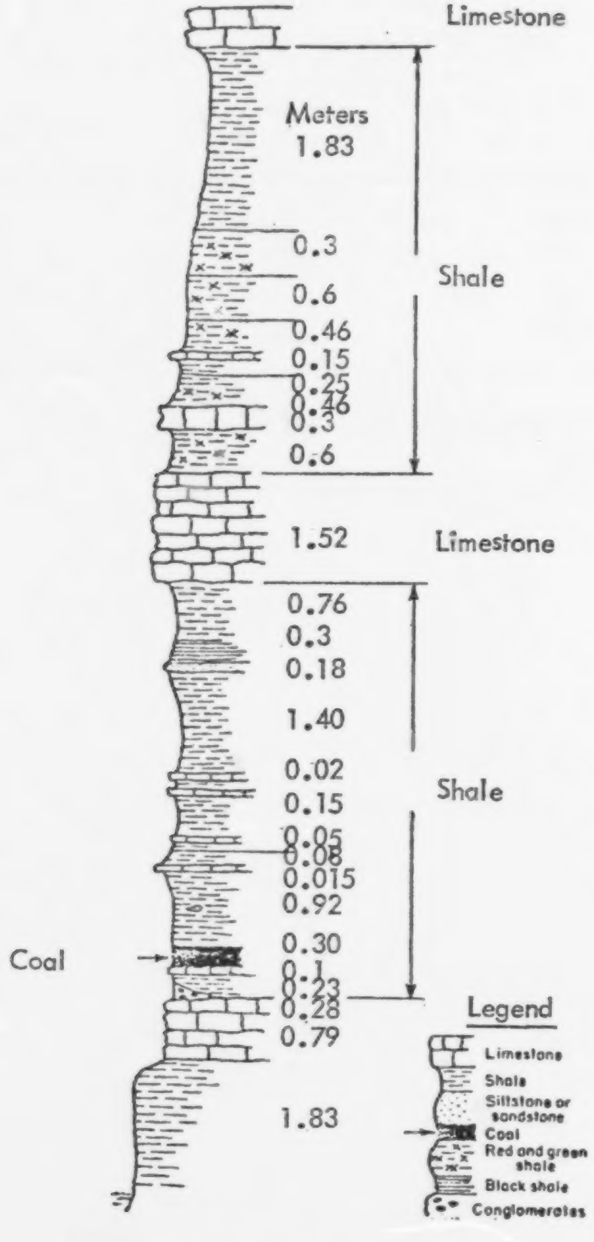

Limestone
Meters
1.83
0.3
Shale
0.6
0.46
0.15
0.25
0.46
0.3
0.6
1.52
Limestone
0.76
0.3
0.18
1.40
0.02
Shale
0.15
0.05
0.08
0.015
0.92
Coal
0.30
0.1
0.23
0.28
0.79
1.83
Legend
Limestone
Shale
Siltstone or sandstone
Coal
Red and green shale
Black shale
Conglomerates

Figure 19. Stratigraphic section of a typical coal mine.

Source: 106.

TABLE 34. REPRESENTATIVE THICKNESS OF COAL MINE SIMULATION TEST COLUMNS

Material	Representative Stratum Thickness (m)	Column Layer Thickness (m)	Scale Coefficient[a]
Bituminous Coal	9.45	0.611	15.5
Limestone[b]	7.32	10.46	15.8
Claystone[c]	2.13	0.551	3.9
Sandstone[c]	11.58	10.73	15.8

[a] Thickness of layer in field to thickness of simulated layer in column.
[b] Excludes add-mixed #60 sand.
[c] Includes add-mixed #60 sand from claystone layer.

Source: 106.

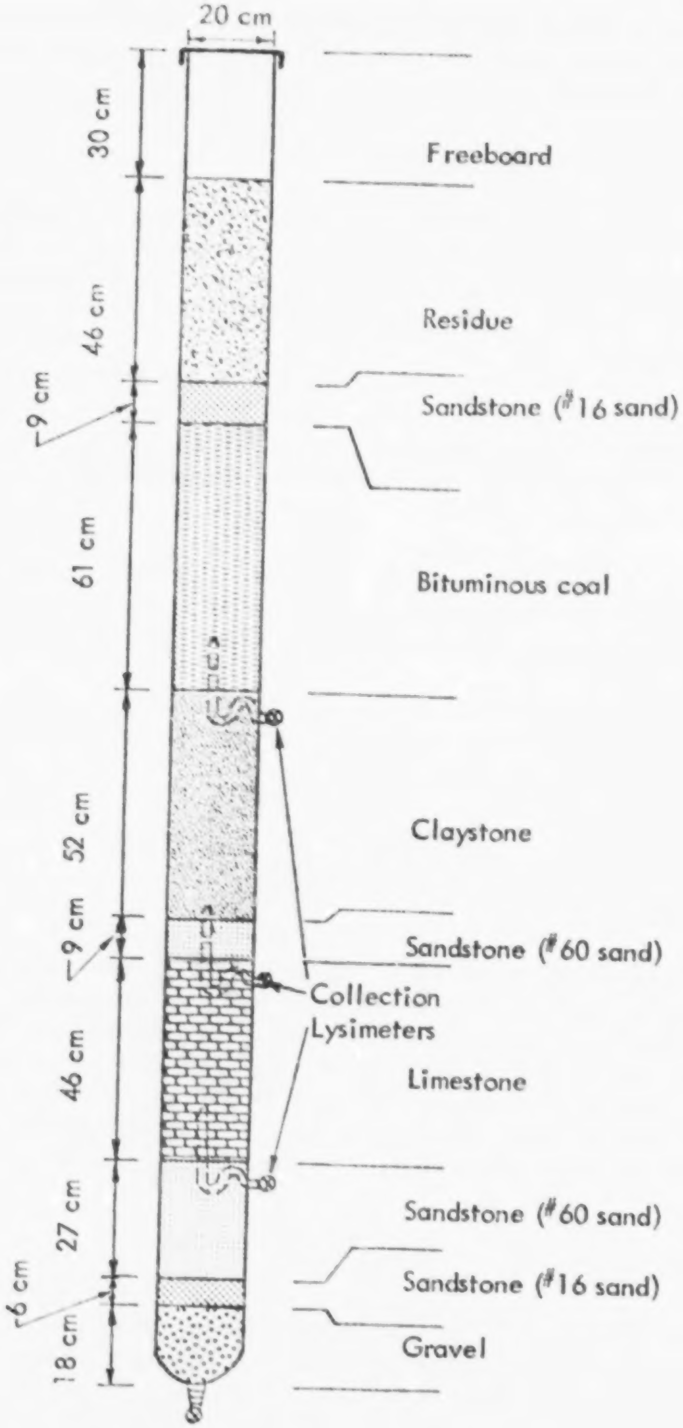

20 cm
30 cm
Freeboard
46 cm
Residue
9 cm
Sandstone (#16 sand)
61 cm
Bituminous coal
52 cm
Claystone
9 cm
Sandstone (#60 sand)
Collection Lysimeters
46 cm
Limestone
27 cm
Sandstone (#60 sand)
6 cm
Sandstone (#16 sand)
18 cm
Gravel

Figure 20. Abandoned coal mine test column.

number 60 sand used in the test column represented the deposited sandy base over which the residues might be placed when filling was initiated. The structure of the ocean test columns is shown in Figure 21.

Sandy, Clayey, and Silty loam Environments

Actual Location. The sandy, clayey, and silty loam soils represent common land disposal environments. Actual samples were found in the field according to the desired classification, and the local in-situ locations established from the USDA-Soil Conservation Service study described in the report, Soils of the Malibu Area.

Test Columns. Silty loam from the Castaic series was selected for the silty loam test soil. Clay from the Cropley series was used for the clayey loam test soil, and very fine sandy loam from the Huerhuero series for the sandy loam test soil. Table 35 shows the soil characteristics, and Figure 22 indicates the locations from which these representative soil samples were obtained.

The silty and clayey loam test columns were admixed with number 60 mesh silica sand at a rate of 4:1 sand to soil mixture by weight, to achieve satisfactory leachate drainage. The strata configuration for the test columns is shown in Figure 23.

The 4:1 sand-to-soil mixture was also used in the other columns as a permeable, relatively inert "filler." This allowed leachate movement through the simulated subsurface environments.

Pilot Test Column Construction

Column Preparation

A PVC pipe (20.3 cm ID) which was cut to a 3.05 m length served as a test column. The simulated environment was marked on the column, as were locations for layer interfaces, observation ports and soil moisture (lysimeter) ports. The lysimeter and observation ports (2.54 cm diameter) were drilled in the column sides. A 1.59-cm port was drilled in the center of the PVC bottom cap for each column, with a plastic drain spout glued into place. After the columns were washed, cleaned and dried, the bottom cap was glued to the pipe walls. Finally, the columns were bracketed in a vertical position to a supporting wall and backfilled.

Column Material Preparation

Most of the column fill materials were usable when delivered. However, due to the impervious characteristics of the extremely fine-grained claystone, it was apparent that the 100 percent claystone and other impervious layers would not permit practical leachate drainage. Permeability tests were performed on several different ratios of sand and clay mixtures. The mix that provided a reasonable permeability coefficient, employed a ratio of about a 3:1 by weight ratio of number 60 mesh silica sand to clay. Homogeneous

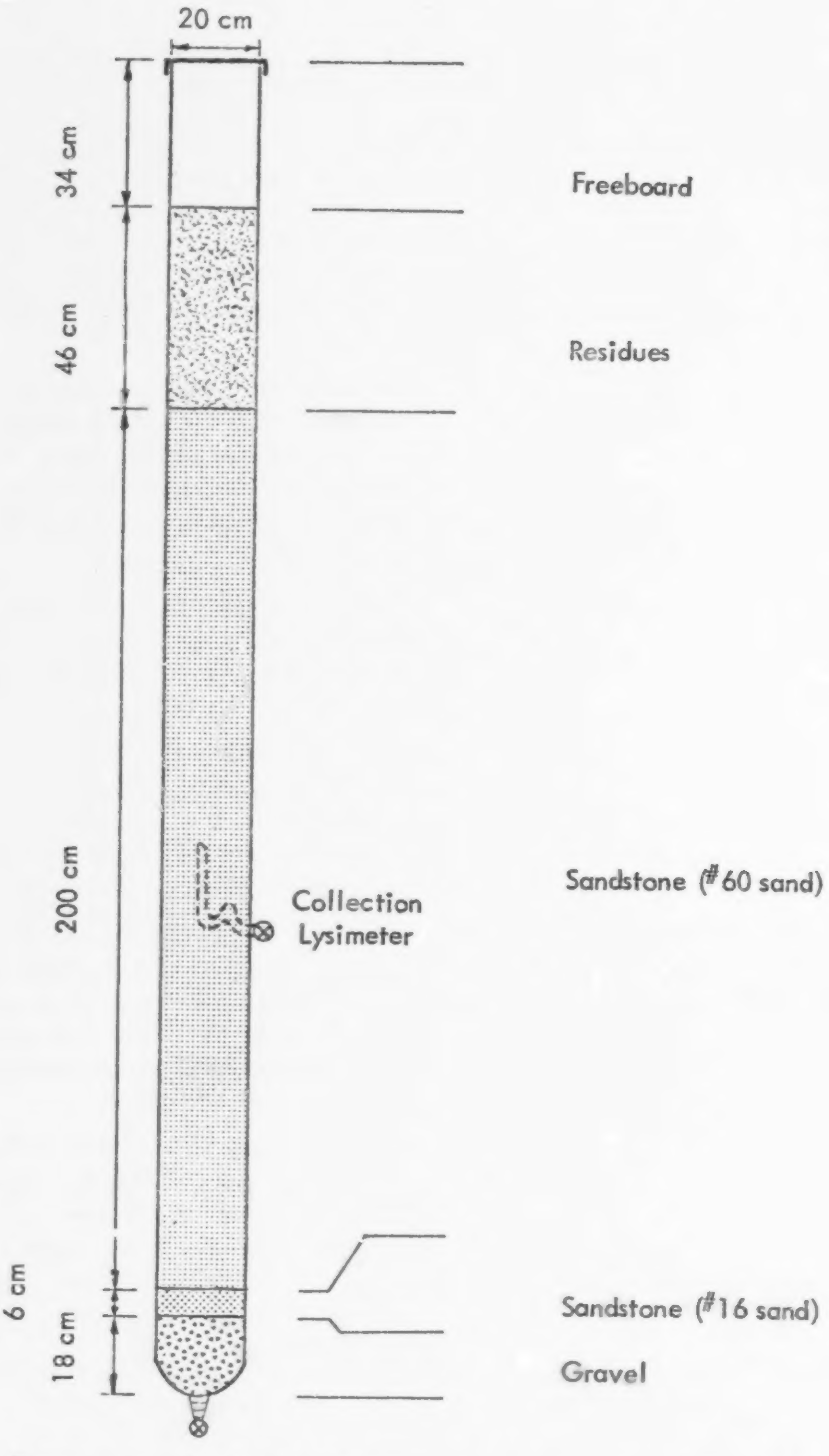

20 cm
34 cm
46 cm
200 cm
6 cm
18 cm
Freeboard
Residues
Collection Lysimeter
Sandstone (#60 sand)
Sandstone (#16 sand)
Gravel

Figure 21. Simulated sedimentary environment: sea water test column.

TABLE 35. TEST COLUMN SOILS CHARACTERISTICS

Series	Horizon (cm)	Characteristics
Castaic Clay Loam Soil	A 0 - 25	Dry color grayish-brown or light brownish-gray to light yellowish-brown or light olive-brown. Textures are silty clay loam. Noncalcareous with reactions from slightly acid to moderately alkaline. Moderate fine granular structure; hard, sticky, and plastic.
	B 25 - 71	Dry color very pale brown or pale yellow to yellow and light olive brown. Textures similar to horizon A with up to 30 percent (by volume) shale fragments. Calcereous with reactions from neutral to moderately alkaline. Weak fine granular structure; hard, sticky, and plastic.
Cropley Silty loam Soil	A 0 - 36	Dry color of dark gray and very dark gray. Textures of clay to silty clay. Reaction is neutral to mildly alkaline. Medium angular blocky structure; very hard, very sticky, and very plastic.
	B 36 - 96	Colors are dark gray, gray, dark grayish-brown, grayish-brown, olive-brown, and yellowish-brown. Texture ranges from clay to clay loam. Calcareous in the lower section, with reaction from mildly to moderately alkaline. Coarse angular blocky structure; very hard, very sticky, and very plastic.
Huerhuero Sandy loam Soil	A 0 - 10	Colors are grayish-brown, light brownish-gray, pale brown, and brown. Textures are fine sandy loam to loam. Reaction is medium acid to neutral. Fine granular massive structure; slightly hard, non-sticky and non-plastic.
	B 10 - 64	Colors are dark brown, dark yellowish-brown, brown and strong brown. Texture is sandy clay to clay, with up to 15 percent gravels in the lower portion. Reaction is neutral to moderately alkaline and calcareous in the lower portion. Medium to coarse angular blocky structure; very hard, slightly sticky, and slightly plastic.

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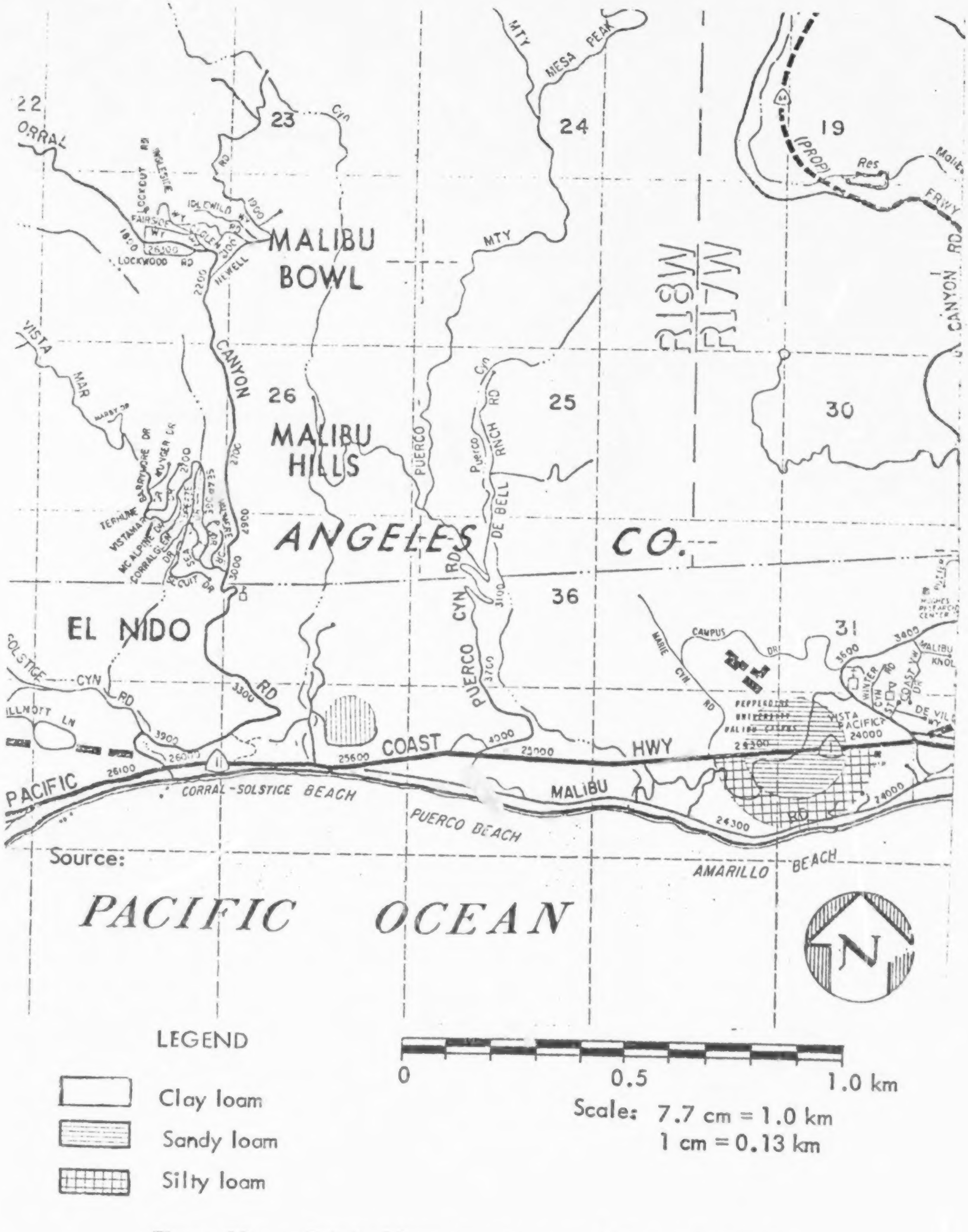
22
ORRAL
23
Cyn
24
MTY
MESA PEAK
19
(PROP)
Res
Malibu
FRWY
LOCKOUT
IDLEWILD
FAIRSIDE
LOCKWOOD RD
NEWELL
MALIBU
BOWL
MTY
R18W
R17W
CANYON RD
VISTA
MAR
CANYON
26
MALIBU
HILLS
PUERCO
Cyn
RD
Puerco
RNCH
25
30
DE BELL
TERHUNE
VISTAMAR
MC ALPINE
CORRALGLEN
ANGELES
CO.
36
CYN
RD
EL NIDO
SOLSTICE
CYN
RD
RD
3300
PUERCO
CAMPUS
DR
MARIE
CYN
RD
31
HUGHES
RESEARCH
CENTER
MALIBU
KNOLL
WINTER
CYN
RD
COAST VW DR
VISTA
PACIFICA
24000
DE VILLE WY
PEPPERDINE
UNIVERSITY
MALIBU CAMPUS
ILLMOTT LN
3900
26100
25600
COAST
4000
25000
HWY
24300
PACIFIC
CORRAL-SOLSTICE BEACH
MALIBU
PUERCO BEACH
24300
RD
24000
AMARILLO
BEACH
Source:
PACIFIC
OCEAN
N
LEGEND
☐ Clay loam
▤ Sandy loam
▦ Silty loam
0
0.5
1.0 km
Scale: 7.7 cm = 1.0 km
1 cm = 0.13 km

Figure 22. Original location of representative soil samples.

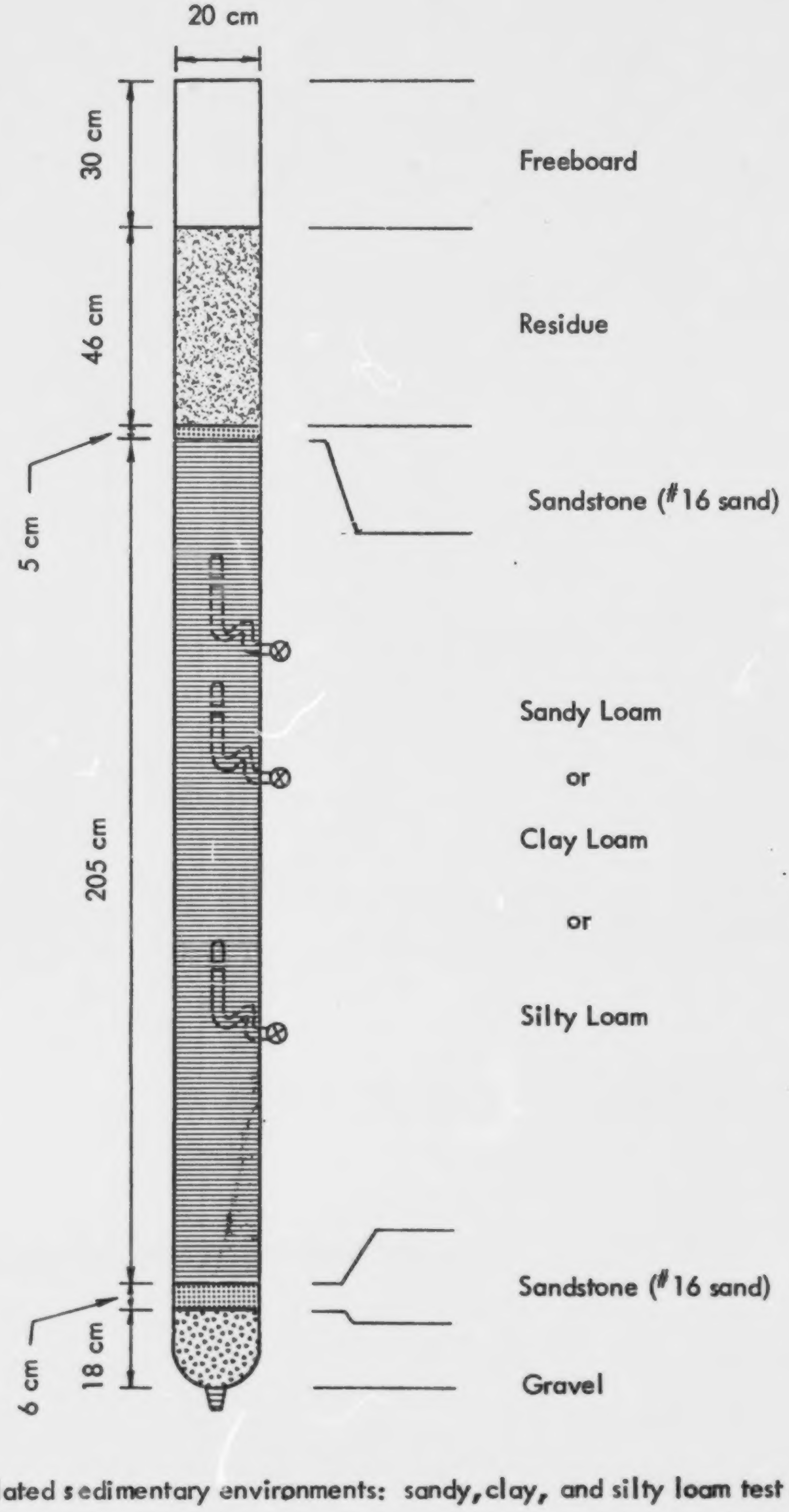
20 cm
30 cm
Freeboard
46 cm
Residue
5 cm
Sandstone (#16 sand)
Sandy Loam
or
Clay Loam
or
Silty Loam
205 cm
Sandstone (#16 sand)
6 cm
18 cm
Gravel

Figure 23: Simulated sedimentary environments: sandy, clay, and silty loam test column.

batches were prepared in 5 to 10 kg quantities which were more easily handled. The granitic limestone and other rock materials also required crushing to achieve the desired permeability.

Standard particle size analyses were performed on all materials added to the test columns (see Figures 10 through 14). Detailed grading analyses and other tests were performed in order to establish practical design parameters which would accomplish the following: 1) prevent movement and clogging (piping of finer material into the coarser materials); 2) provide sufficient permeability to allow accelerated leaching; and 3) assure classified reproducible grain sizes of standard materials. Table 36 presents the criteria used, and Table 37 summarizes the results of the grading analysis.

The bulk densities were determined for the column materials, and these values were compared with known densities of materials that exist in the field (see Table 38). Field densities of typical construction materials were obtained from various dependable sources. The densities of materials in the test columns were calculated using the actual weights of materials added, divided by the volume of the filled columns. The ratios of these latter densities indicated (as expected) that the actual densities of the materials placed in the relatively small columns were less than that which normally prevail under field conditions.

As indicated, large-sized raw materials were first prepared by granulation and, hence, provided a greater surface area exposed for accelerated reactions and greater percolation flow than the coarser natural rocks. In the field, the natural rocky materials would have less direct surface area exposed to percolating water moving through the strata. At specific disposal sites, the amount of surface area exposed per meter of strata is a variable that must be determined for: porosity, capillarity,and the extent of fractures and/or permeability for each component subsurface material. Obviously, simplistic comparisons could not be made of surface area exposed per meter of column test material versus the surface area exposed per meter of stratum in the field.

Residue Preparation

In laboratory studies, it was found that when some residues reacted with water, a large amount of heat was released. To avoid heat damage to the columns, weighed amounts of residues were first placed in an inert container to which water had been added so as to slake and dissipate the heat of reaction.

Column Filling

A filter paper (20.3 cm diameter,number 1 qualitative) with a plastic screen on top (20.3 cm diameter) was placed in the bottom of the column. These items were installed from the top and their location adjusted with a long pole to obtain their correct position. The columns were then ready for partial filling.

Each column was filled with materials to simulate various strata in the quantities shown in Table 39, and according to the depths established during the literature search. Care

TABLE 36. CRITERIA DEFINITION FOR GRADING ANALYSIS

Objective	Criteria[a,b]
1) Prevention of erosion and clogging (piping of finer material through coarser material)	$\frac{D_{15}\ (\text{filter})}{D_{85}\ (\text{soil})} < 4$ to 5
2) Permeability sufficient to prevent the buildup of large seepage forces	$\frac{D_{15}\ (\text{filter})}{D_{15}\ (\text{soil})} > 4$ to 5
3) Approximately parallel grain size curves	$\frac{D_{50}\ (\text{filter})}{D_{50}\ (\text{soil})} \leq 25$

[a] D_x = diameter such that x percent of material is finer.

[b] filter = layer above, soil = layer below.

Source: 25,154.

TABLE 37 . COLUMN MATERIALS GRADING ANALYSIS

Soil \ Filter	Limestone	Dolomite	#16 Silica Sand	#60 Silica Sand	P-Gravel	Coal	Claystone 4:1	Granite Bedrock 1:1	Granite Bedrock 3:1
Limestone			2 Marg.[a,b]	2		2 Marg.	2		
Dolomite			2 Marg.	2	1		2		
#16 Silica Sand	2	2		2	o.k.	2		2	2
#60 Silica Sand	2	2 Marg.	2 Marg.		1,3	2 Marg.		2 Marg.	3
P-Gravel	2	2	2	2		2			
Coal	2		2 Marg.	2	o.k.		2		
Claystone 4:1				o.k.					
Granite Bedrock 1:1			2 Marg.	2	o.k.				
Granite Bedrock 3:1			2	2	o.k.				

[a] Numbers indicate grading analysis criteria definition shown in Table 34 .

[b] Marg. = Marginal .

TABLE 38 . MATERIAL DENSITIES OF NATURAL STRATA AND TEST COLUMNS

Material	Wt. Added (Kg)	Test Column Height (cm)	 Area	 Volume (cu cm)	Density (g/cc)	Density of Field Rocks (g/cc)	Ratio of Densities Column:Field (g/cc)
P-Gravel	12.2	18	314.16	5,654.88	2.16	2.72[d]	0.79:1
#16 Silica Sand	5.4	6	314.16	1,884.96	2.86	2.32[a]	1.23:1
	6.4	9	314.16	2,827.44	2.26	2.32	0.97:1
#60 Silica Sand	27.2	55	314.16	17,278.8	1.57	2.32	0.68:1
	97.7	200	314.16	62,832.0	1.55	2.32	0.67:1
Clay: Sand[b]	22.2	49	314.16	15,393.8	1.44	2.42[c]	0.60:1
	23.6	52	314.16	16,336.3	1.44	2.42	0.60:1
Limestone	50.3	91	314.16	28,588.6	1.76	2.71	0.65:1
	25.9	46	314.16	14,451.4	1.93	2.71	0.71:1
Dolomite	43.1	91	314.16	28,588.6	1.51	2.85	0.53:1
Granite Bedrock	34.9	61	314.16	19,163.76	1.82	2.72[d]	0.67:1
Solid Waste	12.2	61	314.16	19,163.76	0.63	0.594	1.06:1
Bituminous Coal	17.2	61	314.16	19,163.8	0.89	1.25	0.71:1

[a] Sandstone
[b] 1:3 by weight
[c] Shale
[d] Granodiorite

Source: 51,98.

TABLE 39. MATERIALS IN TEST COLUMN LAYERS BY WEIGHT

Column Layers in Order of Addition	Average Weight per Layer by Column Type (kg)							
	Limestone Quarry	Dolomite Quarry	Ocean Disposal	Sanitary Landfill	Coal Mine	Sandy Loam	Clay Loam: sand 1:4	Silty Loam sand 1:3
Pea gravel (.95 cm)						11.3	11.3	11.3
Pea gravel (.64 cm)	12.2[a]	12.2[a]	12.2[a]	12.2[a]	12.2[a]	6.4	6.4	6.8
Silica sand #16	5.4	5.4	5.4	5.4	5.4			
Silica sand #60	27.2	27.2	97.7		13.2			
Clay: #60 sand 1:4	22.2	22.2						
Limestone	50.3				25.9			
Dolomite		43.1						
Granite p-gravel: decomposed granite 3:1				34.9				
Silica sand #16				6.4				
Silica sand #60	4.1	4.1		16.8	4.1			
Clay: #60 sand 1:4				14.1	23.6			
Solid waste				12.2				
Bituminous coal					17.2			
Soil horizon B						80.5	88.9	76.9
Soil horizon A						17.9	15.0	12.5
Silica sand #16				8.2	5.4			

[a] Columns 21–30 contain 6.8 kg of 0.95 cm gravel covered by 5.4 kg of 0.64 cm gravel.

was taken to add the bottom pea gravel layer slowly to avoid damage to the column's bottom filter and screen. Column interface level depths were measured with a weighted string held from the top or through an observation port. The placed layers were checked to ensure that there was a level thickness from the center of the column to the circumference.

During column filling, the leachate collection lysimeters were placed in the test columns as shown in Figures 16 to 18, 20,21, and 23, with the lysimeter generally located in the layer above the collection tube opening. Each lysimeter was made from a (1-bar) porous ceramic cup which was attached to a 30.5 cm length of polyethylene tubing (1.27 cm ID). The ceramic cup and 3 to 5 cm of the tubing were then covered with a 0.64 cm layer of number 200-mesh silica sand, applied in a thick slurry. The ceramic lysimeters were placed in a surrounding Ottawa-type fine sand bed held in place by a cotton bag. Filling of material was stopped just below each column opening, and the lysimeter assembly was then lowered in place with a nylon string. The outlet tube was threaded through the column wall hole, and a rubber stopper was placed on the outlet tube and then secured in the hole (see Figure 24 for the lysimeter schematic assembly and its placement in the columns). The lysimeter elevation was adjusted above the outlet port. Column filling was then resumed. When the lysimeters were covered with compacted materials to a depth of 15 cm or more, the string was removed. For the soil environment test columns, the leachate lysimeters were left attached to the string for several days while the columns were flushed with tap water, and the simulated strata thus compacted. After washing the test columns (see the following section) filter paper (20.3 cm diameter, #1 qualitative) was placed in the columns above the stratum materials and the residue was added. The quantities of the fluidized-bed residues added to each column are shown in Table 40. The external leachate drainage collection tubing and storage flasks, connectors, and manifold were installed as shown in Figure 25.

Sample Bottle Labeling

Each lysimeter was provided with its own sample collection flask, labeled with the appropriate identifying column outlet number. All lysimeters, drains, and columns were uniformly identified sequentially from the bottom of the column up, starting with the bottom drain. Leachate sample collection bottles were placed and labeled according to the following code sequence: column number, column abbreviation, lysimeter letter, and lysimeter location; a typical leachate column sample label was as follows: 2 LQ-C-top lysimeter.

Column Washing

Before adding the test residues and monitoring the leachate reactions, the strata materials in each column were flushed with tap water to establish the column's base-line leachate quality and flow quantity. Tap water was added daily for at least two weeks until the laboratory chemical analysis revealed a nearly constant level of leached constituents.

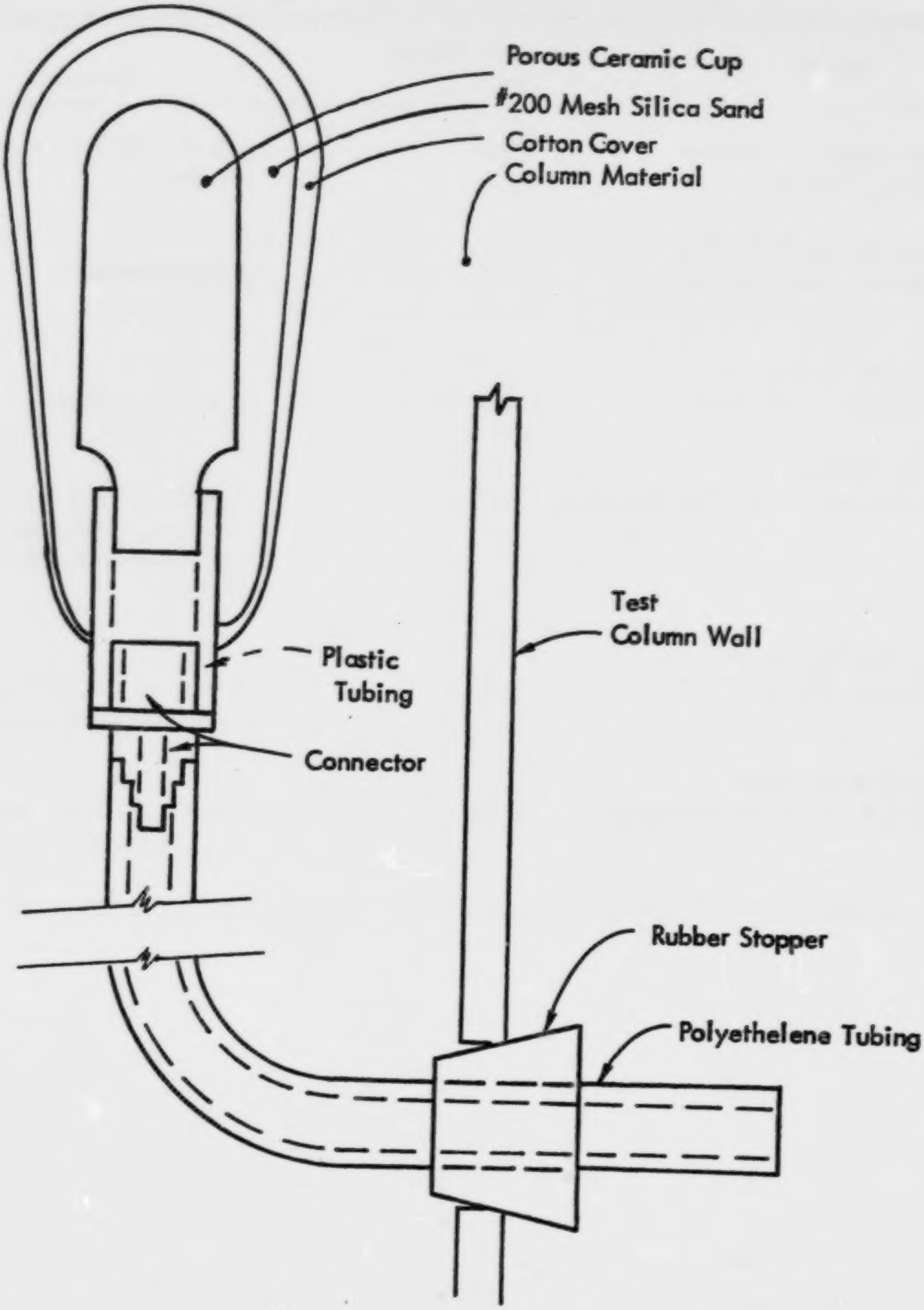
Porous Ceramic Cup
#200 Mesh Silica Sand
Cotton Cover
Column Material
Test Column Wall
Plastic Tubing
Connector
Rubber Stopper
Polyethelene Tubing

Figure 24. Lysimeter construction and test column placement.

TABLE 40. RESIDUES ADDED TO COLUMNS

Residue Type	Quantity Added (kg)	Remarks
Pope, Evans, & Robbins Virginia Fly Ash	9.07	slaked with 3.8 l water over two days.
Pope, Evans, & Robbins Virginia Spent Bed Material	13.61	unslaked weight.
Exxon Miniplant New Jersey Fly Ash	13.61	unslaked weight.
Exxon Miniplant New Jersey Spent Bed Material	9.98	slaked with 7.6 l water over two days, slaked (dry) weight. Equivalent unslaked weight, 8.7 kg.
Esso Gasifier Plant England Fly Ash	11.34	slaked with 3.8 l water over one day, unslaked weight.
Esso Gasifier Plant England Spent Bed Material	6.35	slaked with 3.8 l over one day, unslaked weight.

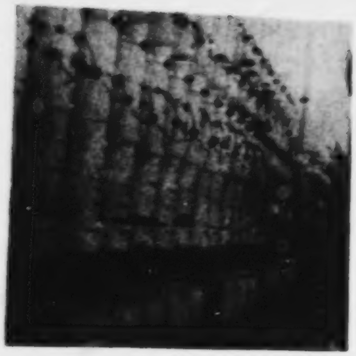

Figure 25. Outdoor columns leachate sampling apparatus.

To determine the flow rate characteristics of each column, the outlet drains were kept open for two days following each water addition until there was no further leachate flow into the drain. A volume of 7.6 liters of tap water was added each time to the column inlet, and the rate of water leached for each time period was intermittently measured over a period of 27 to 30 hours. In Column 14, the residue quickly solidified, in situ, in spite of the bench scale tests, and the water was perched over the top layers. This column was immediately repacked with a larger sand mixture to eliminate the percolation obstruction. All the columns were thus successfully proven to initially drain percolated water. Typical column percolation data are shown in Figures 26 to 30. Each residue sample was then mixed with the standard Ottawa sand to achieve a known permeable condition, and then placed in the test columns on top.

Leachate Sampling and Analyses

Water Addition

Tri-weekly (every Monday, Wednesday, and Friday afternoons) a chemically known potable water (see Table 41) was routinely added to all columns, except for the ocean disposal columns which received sea water (see Tables 42 and 43). The low TDS potable water was employed to simulate natural conditions since most drainage runoff contains similar dissolved solids. The potable water supply source was natural runoff. All clamps on drains were closed before the fresh or sea water was added, and the water was retained in the columns through the next sampling day. Ideally, 7.6 liters of water were added each time. However, some columns gradually reduced their drainage after several months so that they received less than 7.6 liters at the top of the column. Procedures for the sea water columns were changed after six months to investigate leaching in a flooded environment, i.e., the sea water columns were kept saturated except for partial surface drainage which allowed the addition of fresh sea water. The purpose of the flooding test was to simulate the addition of a residual landfill into an ocean environment rather than in the former tidal prism environment.

Leachate Sampling Procedure

Leachate samples from the column drains and lysimeters were collected to analyze the results of the previous day's water addition.

1. During weeks one through 52, the lysimeters and the drains were sampled Monday, Wednesday, and Friday. After week 52, only the drains were sampled once a week on Friday.

2. In the morning, the column lysimeters were sampled simultaneously using a system of interconnecting tubing and flasks linked to a vacuum pump. Figure 31 illustrates a schematic of a typical test column leachate collection system. A vacuum of about 635 mm of mercury applied for five to six hours normally provided sufficient sample for analyses. If there was insufficient sample at the end of the day, pumping was maintained until the amount needed for the analyses was obtained. Conversely, the leachate valves were

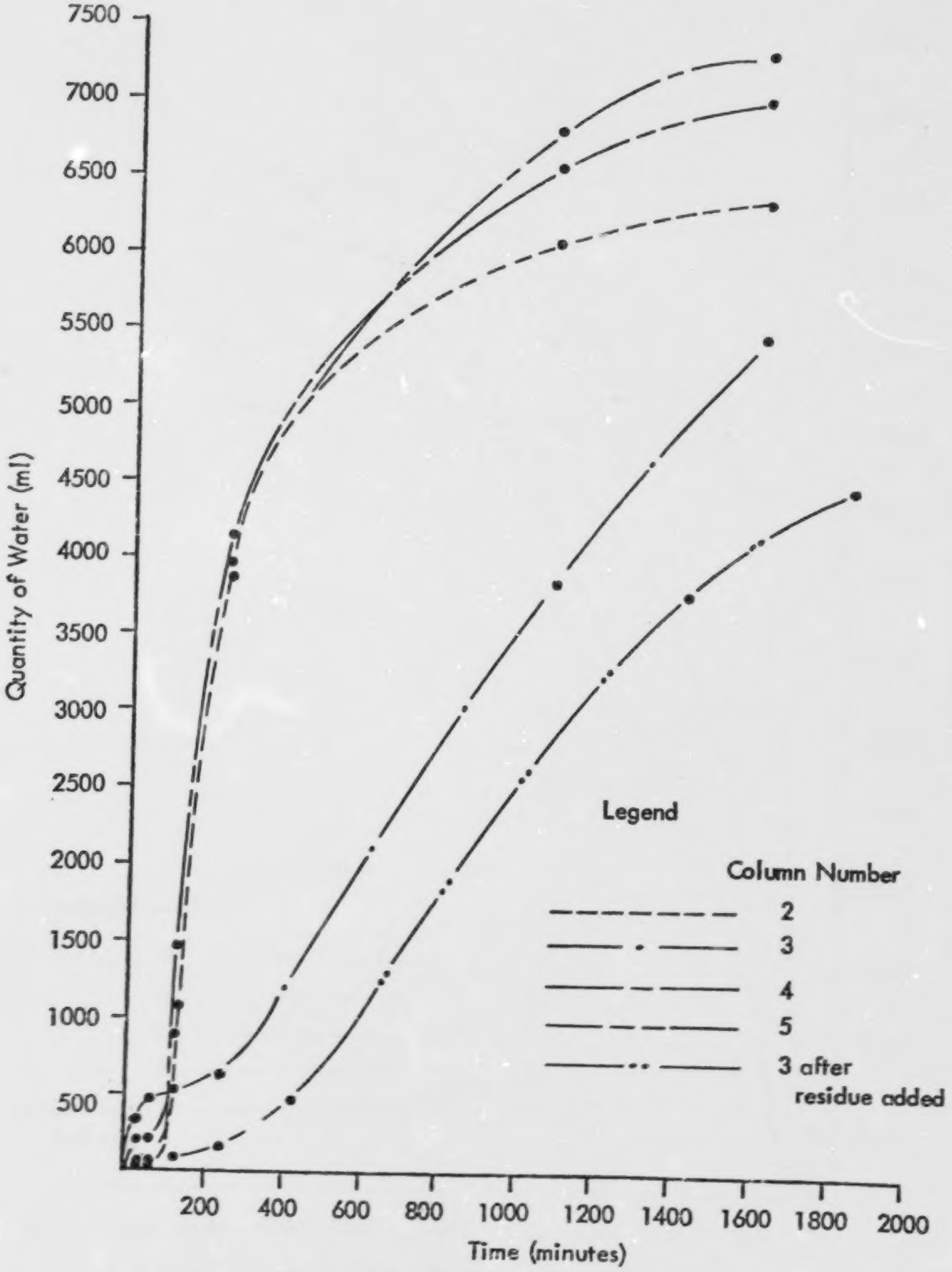

Figure 26 . Drainage through limestone quarry columns.

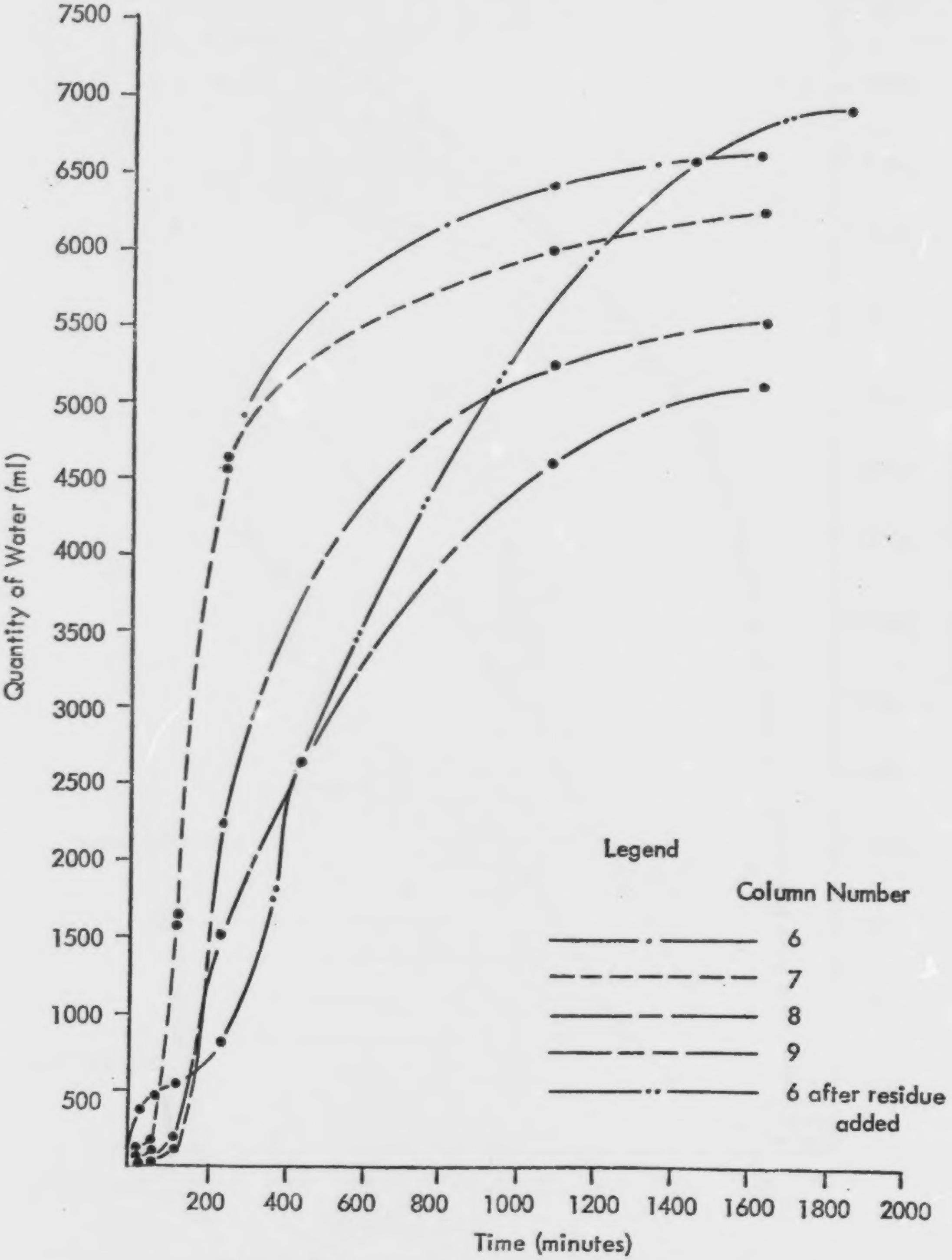

Figure 27. Drainage through dolomite quarry columns.

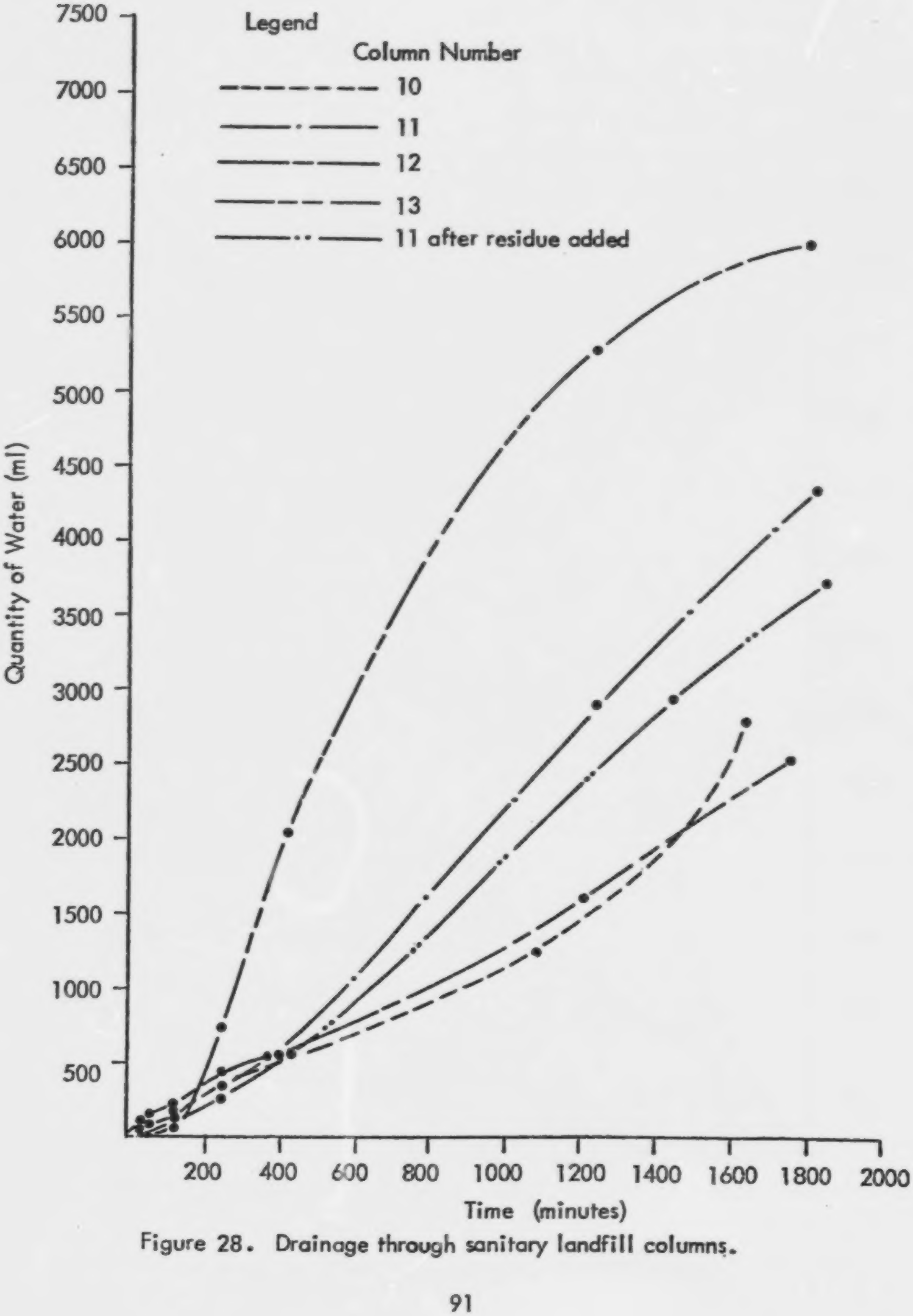

Figure 28. Drainage through sanitary landfill columns.

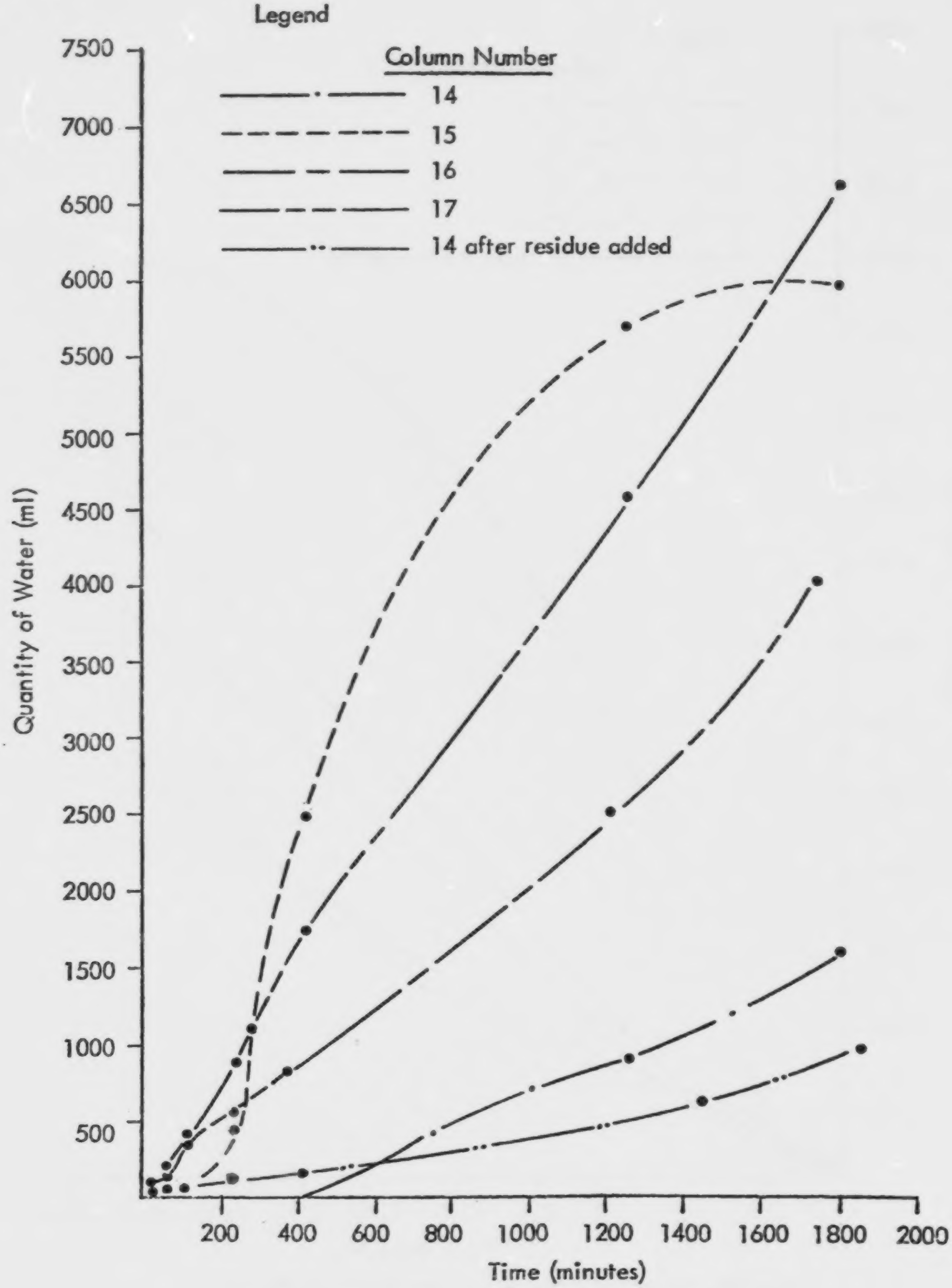

Figure 29 · Drainage through coal mine columns.

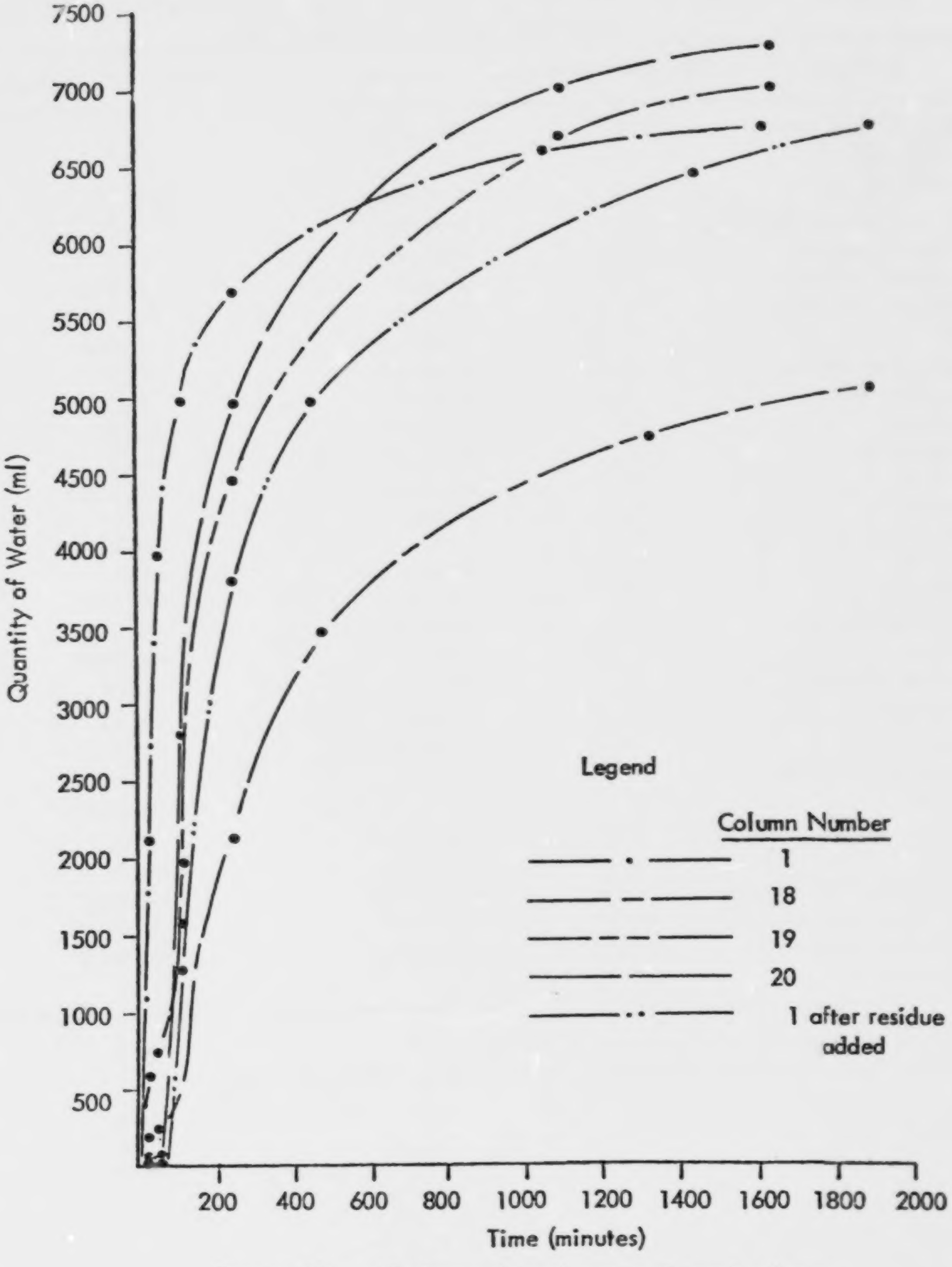

Figure 30 . Drainage through ocean disposal columns.

TABLE 41. COMPLETE ANALYSIS OF LOS ANGELES OWENS RIVER AQUEDUCT (POTABLE WATER) COLUMNS TEST

Analysis	1975–1976 Averages[a]	Analysis	1975–1976 Averages[a]
Spec.Elec. Cond. (K x 10^6)	299	Aluminum	0.07
TDR (Calc.)[b]	184	Antimony	<0.01
Total Hardness ($CaCO_3$)	79	Arsenic	0.02
Color (apparent)	8	Barium	0.1
Turbidity (units)	3.2	Bismuth	0.003
Temperature (°C)	14.5	Bromide	<0.1
pH	7.95	Cadmium	<0.002
Saturation index	-0.30	Chromium	0.01
Stability index	8.55	Copper	0.06
Calcium	24	Cyanide	<0.01
Magnesium	5.0	Detergents (MBAS)	<0.05
Sodium	30	Gallium	<0.0002
Potassium	32	Iodide	0.01
Alkalinity ($CaCO_3$)	109	Lead	0.01
Sulfate	20	Manganese	<0.01
Chloride	13	Mercury	<0.0001
Nitrate (NO_3)	0.8	Molybdenum	0.005
Boron	0.34	Nickel	<0.0009
Carbon dioxide	3	Phenol	<0.001
Fluoride	0.52	Phosphate (PO_4)	0.16
Iron	0.09	Selenium	<0.002
Oxygen (dissolved)	8.9	Silver	<0.02
Silica	22	Tin	0.0005
BOD_5	1.7	Titanium	0.002
COD	4	Tungsten	<0.07
Nitrogen, TKN (as N)	0.10	Vanadium	0.002
Nitrogen (ammonia)	<0.01	Zinc	0.01
Nitrogen (nitrite)	<0.001	Zirconium	<0.0003
Nitrogen (nitrate)	0.18		

[a] Chemical results in mg/l, except as noted.

[b] Total dissolved residue = Anions + Cations + CO_3 + $HCO_3^-/2$ + SiO_2.

Source: 185.

TABLE 42. CONSTITUENTS PRESENT IN SEA WATER

Constituent	Cl = 19.00 °/oo[a] mg/kg	Constituent	Cl = 19.00 °/oo mg/kg
Chloride	18,980	Iron	0.002-0.02
Sodium	10,560	Manganese	0.001-0.01
Sulfate	2,650	Copper	0.001-0.01
Magnesium	1,270	Zinc	0.005
Calcium	400	Lead	0.004
Potassium	380	Selenium	0.004
Bromide	65	Cesium	0.002
Carbon	28	Uranium	0.0015
Strontium	13	Molybdenum	5×10^{-4}
Boron	4.6	Thorium	5×10^{-4}
Silicon	0.02-4.0	Cerium	4×10^{-4}
Fluoride	1.4	Silver	3×10^{-4}
Nitrogen (comp.)	0.01-0.7	Vanadium	3×10^{-4}
Aluminum	0.5	Lanthanum	3×10^{-4}
Rubidium	0.2	Yttrium	3×10^{-4}
Lithium	0.1	Nickel	1×10^{-4}
Phosphorous	0.001-0.10	Scandium	4×10^{-5}
Barium	0.05	Mercury	3×10^{-5}
Iodide	0.05	Gold	6×10^{-6}
Arsenic	0.01-0.02	Radium	$0.2\text{-}3.0\times10^{-10}$

[a] Cl=19.00 °/oo denotes a chlorinity of 19.00 parts per thousand.

Source: 190

TABLE 43. SEA WATER APPLIED TO THE TEST COLUMNS

Constituent	1976-1977 Averages
	mg/l
Sulfate	2368
Iron	2.1
Nickel	0.7
Lead	3.0
Zinc	0.2

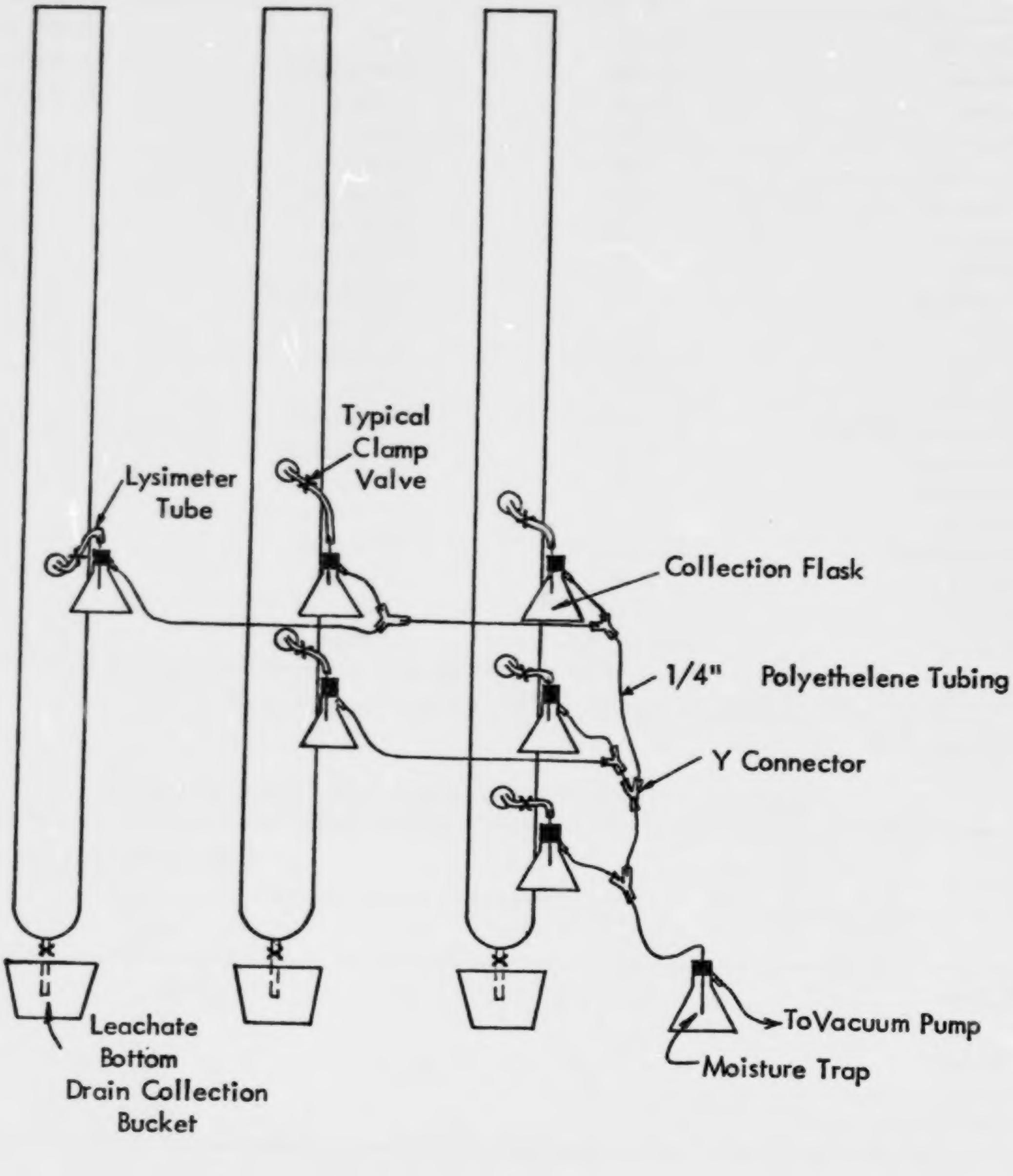
Typical Clamp Valve
Lysimeter Tube
Collection Flask
1/4" Polyethelene Tubing
Y Connector
ToVacuum Pump
Moisture Trap
Leachate Bottom Drain Collection Bucket

Figure 31. Typical test column leachate collection system schematic.

shut off sooner than the five to six hours if sufficient amounts of sample were obtained in order to maintain a simulated groundwater profile.

3. After the vacuum pump was started, a graduated collection container was placed beneath each drainage tube, and the drainage valve was opened.

4. At the end of the day, the amount of leachate collected in each container was noted and the leachate sample was taken.

5. Equal amounts of daily samples were composited to make up each weekly sample of 250 ml. These composite samples were used for the laboratory analysis.

6. After sampling, all outlet vales for the lysimeters and the drains were closed and tap or ocean water was applied to the columns as described above.

Leachate Analyses

During the first 25 weeks of each column's operation, weekly composites were sampled; thereafter, the frequency of laboratory sampling was reduced to one per each two-week period, and after 32 weeks, to one per each four week period. During the first 40 weeks, pH, specific conductance, total dissolved solids, chloride, sulfate, iron, nickel, lead and zinc were analyzed at the request of the EPA project officer. Beginning on week 40, additional constituents were analyzed. These were aluminum, boron, calcium, cadmium, copper, mercury, nitrate, total organic carbon, and chemical oxygen demand. The monthly composite samples were collected and analyzed during the first 65 weeks of column operation; however, only drain samples were collected thereafter because of increased costs. All the drain samples following the 53rd week were composited over a four-month period before chemical analysis in order to reduce costs. Each composite sample was analyzed according to the EPA recommended procedures, referenced in Appendix A. The analytical results of the test column leachate analyses were then statistically evaluated using a HP 9830A computer. The statistics included average values, percent removal from each stratum layer, computerized plotting of constituent concentration versus water applied, and comparison of the constituents with the water quality criteria.

Column Operation During Testing

After the pilot test columns had been in operation for approximately one year, the fluidized-bed mixtures and the clay stratum consolidated and reduced the percolation significantly. Furthermore, the leachate precipitated minerals on the ceramic lysimeters and caused fouling. Because the quantity of leachate sampled from many of the columns was insufficient for analyses, those columns were dismantled and repacked after correcting the problems. Columns 1,2,3,6,8,10,14,17,26,28, and 33 through 36 were thus dismantled. Two factors induced restriction of the water percolation in the columns: first, hardening of the residue at the top of the column and, second, consolidation of the simulated clay type sedimentary materials. Thus, the percolation was eventually reduced to the point that it prevented movement of the leachate.

In summary, the dismantled columns 1,8,33,and 34 appeared to contain hardened residues; columns 2,3 and 14 showed hardened column stratum material; and columns 33,34, and 36 showed some signs of fouled lysimeters. The columns were rebuilt with new lysimeters and sand, and put into operation.

After the first few weeks of operation, many of the columns began leaking in the proximity of the lysimeter ports but they were promptly repaired. Leaks also developed occasionally throughout the column test period, and were immediately fixed. After the conclusion of the pilot columns' tests, all the columns were dismantled and inspected. These observations are summarized in Table 44. The NJFA in all but the dolomite and the soil environments had hardened into a rock-like state. The NJFA in the dolomite test column was firm, but sandy. The VSBM and the ESBM residues in the limestone, dolomite, and sanitary landfill columns (except ESBM in the sanitary landfill column), and the EFA in the limestone environment were found to be soft and clayey in texture. In each of the other test columns, the residue was found to be sandy in appearance. The claystone sand mixture layers in the test-columns were generally moderately consolidated in texture. Exceptions included limestone and dolomite test columns containing the NJFA residue which was not consolidated. The sanitary landfill environments emitted a septic-type of odor and had blackened the claystone layer lying directly below the sanitary landfill. The sandy soil test column containing EFA had blackened and emitted a septic type odor.

Results and Statistical Evaluation

The average and maximum values, shown in Table 45 to 50 summarizes the results obtained from over 80 weeks of the test columns operations. In general, the results show that the fluidized-bed residues from the pilot plants operated at Exxon, Linden, New Jersey and Pope, Evans, and Robbins, Alexandria, Virginia leached lower chloride and greater sulfate concentrations than the residues obtained from Esso, Great Britain. The sandy, clayey, and silty soils test columns leached higher concentrations of chlorides and iron than did the other types of simulated environments. Lastly, the simulated sanitary landfill leached much less sulfates, particularly from the VFA, than the other test columns. Further evaluations of the analytical results are presented in the following paragraphs.

Rainfall Analogy

The analytical results of the pilot test columns were equated to potential natural disposal sites. This was done by establishing a direct relationship between the actual volume of water applied to the test columns and the rainfall one might expect in a specific natural environment. The total volume applied to each test column during the duration of this study varied from 170 to 1200 liters because of consolidation and hydrolization of some residues and strata materials. Also, test columns were set up at a later date; consequently, the water applied to these columns was considerably less than the 900 to 1200 liters applied to the earlier columns. Therefore, a constant volume of applied water was established. Over 250 l were added to all but one of the test columns; thus, a 250 l applied

TABLE 44 . SUMMARY OF FLUIDIZED BED COMBUSTION COLUMN CONTENTS

Environment	Residue	Physical State of Residue			Comments
		Moisture	Consistency	Appearance	
Limestone	NJFA	Medium	Hard	Rocky	No hard material in the other layers
Limestone	NJSBM	Medium	Loose	Sandy	Claystone layer was moderately hard
Limestone	VFA	Medium	Loose	Sandy	Claystone layer was moderately hard
Limestone	VSBM	Medium	Soft	Clayey	Claystone layer was moderately hard
Limestone	EFA	Medium to high	Soft	Clayey	Claystone layer was moderately hard
Limestone	ESBM	Medium to high	Soft	Clayey	Claystone layer was moderately hard
Dolomite	NJFA	Medium to high	Firm	Sandy	No hard material in other layers
Dolomite	NJSBM	Medium	Soft	Clayey	Claystone layer was moderately hard
Dolomite	VFA	Medium	Loose	Sandy	Claystone layer was moderately hard
Dolomite	VSBM	Medium	Soft	Clayey	Claystone layer was moderately hard
Dolomite	EFA	Medium to high	Soft	Sandy	Claystone layer was moderately hard
Dolomite	ESBM	Medium to high	Soft	Clayey	Claystone layer was moderately hard

TABLE 44 (continued)

Environment	Residue	Physical State of Residue Moisture	Consistency	Appearance	Comments
Sanitary Landfill	NJFA	Medium	Hard	Rocky	Landfill layer was black with septic type odor. Claystone layer was moderately hard
Sanitary Landfill	NJSBM	Medium	Soft	Sandy	Landfill layer was black with septic type odor. Claystone layer was moderately hard
Sanitary Landfill	VFA	Medium	Soft	Sandy	Landfill layer was black with septic type odor. Claystone layer was moderately hard
Sanitary Landfill	VSBM	Medium to high	Soft	Clayey	Landfill layer was black with septic type odor. Claystone layer was moderately hard
Sanitary Landfill	EFA	Medium	Loose	Sandy	Landfill layer was black with septic type odor. Claystone layer was moderately hard
Sanitary Landfill	ESBM	Medium	Loose	Sandy	Landfill layer was black with septic type odor. Claystone layer was moderately hard
Coal Mine	NJFA	Medium	Hard	Rocky	Claystone layer was moderately hard
Coal Mine	NJSBM	Medium	Soft	Sandy	Claystone layer was moderately hard
Coal Mine	VFA	Medium	Loose	Sandy	Claystone layer was moderately hard

TABLE 44 (continued)

Environment	Residue	Physical State of Residue Moisture	Consistency	Appearance	Comments
Coal Mine	VSBM	Medium	Soft	Sandy	Claystone layer was moderately hard
Coal Mine	EFA	Medium	Loose	Sandy	Claystone layer was moderately hard
Coal Mine	ESBM	Medium	Loose	Sandy	Claystone layer was moderately hard
Ocean	NJFA	Medium	Hard	Rocky	No hard material in other layers
Ocean	NJSBM	Medium	Soft	Sandy	No hard material in other layers
Ocean	VFA	Medium	Loose	Sandy	No hard material in other layers
Ocean	VSBM	Medium	Soft	Sandy	No hard material in other layers
Ocean	EFA	Medium	Soft	Sandy	No hard material in other layers
Ocean	ESBM	Medium	Soft	Sandy	No hard material in other layers
Sandy Loam	EFA	Medium	Loose	Sandy	Sandy loam layer was black with septic odor
Sandy Loam	ESBM	Medium	Loose	Sandy	No hard material in other layers
Clay Loam	EFA	Medium	Soft	Sandy	Clay loam layer was quite moist
Clay Loam	ESBM	Medium	Loose	Sandy	No hard material in other layers
Silty Loam	EFA	Medium	Loose	Sandy	No hard material in other layers
Silty Loam	ESBM	Medium	Loose	Sandy	No hard material in other layers

TABLE 45 . VARIATION IN LIMESTONE QUARRY COLUMN LEACHATE CONSTITUENTS

Residue[a] Type	Number of Analyses	Range of Concentration (mg/l)											
		Cl^-		$SO_4^=$		Fe		Ni		Pb		Zn	
		avg	max	avg	max	avg	max	avg	max	avg	max	avg	max
NJFA	33												
Top lysimeter		29	91	1102	1700	0.10	0.42	0.19	0.48	0.11	0.30	0.05	0.21
Bottom lysimeter		26	72	1132	1600	0.11	1.20	0.17	0.38	0.10	0.20	0.07	0.45
Drain		24	70	1231	2000	0.08	0.30	0.18	0.46	0.11	0.40	0.03	0.16
NJSBM	33												
Top lysimeter		32	49	795	1220	0.10	0.30	0.33	0.90	0.17	0.70	0.07	0.45
Bottom lysimeter		32	96	528	970	0.10	0.78	0.22	1.32	0.12	0.60	0.08	0.84
Drain		32	82	517	780	0.07	0.30	0.18	0.78	0.12	0.30	0.03	0.08
VFA	33												
Top lysimeter		34	100	687	1300	0.09	0.40	0.17	0.48	0.13	0.30	0.03	0.10
Bottom lysimeter		26	75	844	1500	0.09	0.60	0.18	1.10	0.10	0.30	0.03	0.09
Drain		23	62	661	1180	0.08	0.80	0.13	0.60	0.09	0.30	0.02	0.05
VSBM	36												
Top lysimeter		34	105	920	1800	0.14	0.60	0.23	0.92	0.29	1.80	0.03	0.13
Bottom lysimeter		30	115	606	1790	0.13	1.20	0.14	0.50	0.15	1.50	0.08	0.85
Drain		30	133	495	1780	0.08	0.50	0.14	1.34	0.12	1.10	0.02	0.08
EFA	24												
Top lysimeter		113	400	903	1340	0.06	0.14	0.24	0.60	0.10	0.30	0.07	0.30
Bottom lysimeter		110	645	599	1180	0.09	0.35	0.30	1.10	0.15	0.60	0.06	0.30
Drain		67	246	618	1800	0.13	1.10	0.24	1.00	0.11	0.30	0.06	0.30
ESBM	24												
Top lysimeter		132	357	506	2250	0.12	0.55	0.37	1.60	0.22	0.60	0.05	0.14
Bottom lysimeter		118	410	357	900	0.11	0.50	0.38	1.40	0.23	0.60	0.07	0.45
Drain		125	700	298	2750	0.12	0.35	0.38	1.50	0.23	0.60	0.06	0.15

[a] See Table 6 for residue identification.

TABLE 46 . VARIATION IN DOLOMITE QUARRY COLUMN LEACHATE CONSTITUENTS

Residue[a] Type	Number of Analyses	Cl$^-$		SO$_4^=$		Fe		Ni		Pb		Zn	
		avg	max	avg	max	avg	max	avg	max	avg	max	avg	max
NJFA	33												
Top lysimeter		28	47	1035	1570	0.12	1.20	0.19	0.51	0.13	0.60	0.03	0.07
Bottom lysimeter		28	55	1094	1670	0.12	0.90	0.20	0.48	0.08	0.20	0.04	0.12
Drain		32	76	1090	1700	0.05	0.60	0.16	0.35	0.07	0.30	0.02	0.07
NJSBM	33												
Top lysimeter		28	87	735	1210	0.13	0.40	0.19	0.51	0.13	0.60	0.03	0.07
Bottom lysimeter		25	87	560	920	0.12	0.90	0.20	0.48	0.08	0.20	0.04	0.12
Drain		27	87	337	700	0.09	0.60	0.16	0.35	0.07	0.30	0.02	0.07
VFA	33												
Top lysimeter		35	172	395	1340	0.11	1.37	0.16	0.46	0.07	0.30	0.04	0.09
Bottom lysimeter		33	160	381	1450	0.12	1.02	0.13	0.34	0.07	0.30	0.04	0.12
Drain		31	140	350	1330	0.08	0.70	0.10	0.37	0.04	0.20	0.02	0.08
VSBM	34												
Top lysimeter		30	60	823	1320	0.16	0.80	0.30	0.85	0.26	1.20	0.07	0.40
Bottom lysimeter		25	50	734	1300	0.07	0.30	0.17	0.34	0.11	0.40	0.05	0.16
Drain		25	54	581	1150	0.07	0.30	0.16	0.65	0.10	0.50	0.03	0.11
EFA	24												
Top lysimeter		299	2418	903	1554	0.09	0.50	0.26	0.60	0.15	0.44	0.06	0.14
Bottom lysimeter		235	2280	591	920	0.08	0.35	0.22	0.60	0.09	0.30	0.04	0.12
Drain		193	1459	433	1260	0.08	0.30	0.16	0.60	0.11	0.30	0.08	0.17
ESBM	24												
Top lysimeter		227	1596	315	2300	0.11	0.75	0.33	1.90	0.17	0.70	0.06	0.21
Bottom lysimeter		181	1459	352	3150	0.12	0.65	0.42	1.60	0.18	0.70	0.09	0.62
Drain		138	555	257	2450	0.12	0.70	0.51	1.90	0.18	0.80	0.07	0.28

Range of Concentration (mg/l)

[a] See Table 6 for residue identification.

TABLE 47 . VARIATION IN SANITARY LANDFILL COLUMN LEACHATE CONSTITUENTS

Residue[a] Type	Number of Analyses	Range of Concentration (mg/l)											
		Cl^-		$SO_4^=$		Fe		Ni		Pb		Zn	
		avg	max	avg	max	avg	max	avg	max	avg	max	avg	max
NJFA	31												
Top lysimeter		68	180	390	1150	-	-	0.22	1.00	0.51	4.70	0.04	0.30
Middle lysimeter		45	163	356	920	-	-	0.19	0.70	0.39	5.50	0.03	0.20
Bottom lysimeter		29	54	602	1140	-	-	0.15	0.50	0.09	0.40	0.03	0.10
Drain		33	79	256	1030	-	-	0.11	0.40	0.07	0.30	0.03	0.20
NJSBM	31												
Top lysimeter		54	127	170	994	-	-	0.20	0.80	0.11	0.60	0.04	0.30
Middle lysimeter		48	122	184	1350	-	-	0.18	0.60	0.10	0.30	0.03	0.20
Bottom lysimeter		37	120	124	878	-	-	0.14	0.32	0.08	0.30	0.05	0.42
Drain		32	76	107	747	-	-	0.14	0.60	0.05	0.30	0.02	0.19
VFA	33												
Top lysimeter		38	150	101	1110	-	-	0.13	0.40	0.09	0.40	0.03	0.30
Middle lysimeter		32	154	86	880	-	-	0.13	0.40	0.06	0.30	0.03	0.20
Bottom lysimeter		31	147	73	735	-	-	0.12	0.68	0.07	0.39	0.04	0.30
Drain		28	84	46	410	-	-	0.11	0.40	0.07	0.22	0.03	0.20
VSBM	36												
Top lysimeter		55	110	280	1285	-	-	0.15	0.70	0.22	1.50	0.04	0.20
Middle lysimeter		48	122	367	1410	-	-	0.18	1.00	0.16	0.70	0.06	1.24
Bottom lysimeter		33	107	414	1370	-	-	0.15	0.60	0.21	1.30	0.03	0.32
Drain		33	105	381	1200	-	-	0.19	1.20	0.15	0.90	0.02	0.09
EFA	24												
Top lysimeter		105	312	653	1150	-	-	0.34	0.90	0.11	0.31	0.05	0.10
Middle lysimeter		135	766	935	1540	-	-	0.34	0.70	0.09	0.30	0.06	0.40
Bottom lysimeter		110	304	950	1500	-	-	0.31	0.70	0.07	0.30	0.08	0.98
Drain		98	633	938	2400	-	-	0.38	1.00	0.07	0.40	0.05	0.21
ESBM	24												
Top lysimeter		150	565	109	680	-	-	0.37	0.60	0.16	0.30	0.09	0.33
Middle lysimeter		111	530	284	2550	-	-	0.38	0.90	0.19	0.50	0.10	0.25
Bottom lysimeter		146	433	319	2750	-	-	0.40	1.00	0.19	0.60	0.10	0.30
Drain		164	475	685	4000	-	-	0.52	1.70	0.19	0.40	0.09	0.40

[a] See Table 6 for residue identification.

TABLE 48 . VARIATION IN COAL COLUMN LEACHATE CONSTITUENTS

Residue[a] Type	Number of Analyses	Range of Concentration (mg/l)											
		Cl^-		$SO_4^=$		Fe		Ni		Pb		Zn	
		avg	max	avg	max	avg	max	avg	max	avg	max	avg	max
NJFA	34												
Top lysimeter		33	87	982	1700	0.17	1.84	0.19	0.55	0.11	0.30	0.09	0.30
Middle lysimeter		31	59	890	1400	0.14	1.32	0.19	0.80	0.10	0.30	0.08	0.55
Bottom lysimeter		29	65	1058	1600	0.08	0.33	0.16	0.56	0.08	0.50	0.02	0.07
Drain		32	65	944	1500	0.09	0.60	0.17	0.75	0.08	0.30	0.03	0.12
NJSBM	34												
Top lysimeter		38	93	799	1160	0.08	0.50	0.19	0.78	0.11	0.40	0.04	0.17
Middle lysimeter		36	156	727	1150	0.11	0.50	0.22	0.90	0.12	0.60	0.05	0.48
Bottom lysimeter		37	88	564	840	0.08	0.40	0.16	0.80	0.06	0.40	0.02	0.12
Drain		34	97	444	880	0.08	0.33	0.22	0.90	0.11	0.50	0.04	0.50
VFA	34												
Top lysimeter		31	90	332	1330	0.07	0.30	0.22	1.84	0.07	0.30	0.05	0.47
Middle lysimeter		31	88	613	1660	0.11	0.45	0.25	2.08	0.15	0.80	0.12	0.62
Bottom lysimeter		25	86	339	1420	0.07	0.20	0.17	2.12	0.06	0.20	0.02	0.11
Drain		30	85	328	1370	0.05	0.48	0.20	1.88	0.08	0.30	0.03	0.09
VSBM	31												
Top lysimeter		48	85	589	1484	0.07	0.30	0.16	0.80	0.17	0.90	0.06	0.80
Middle lysimeter		33	100	439	1380	0.14	1.80	0.17	0.70	0.11	0.60	0.09	0.60
Bottom lysimeter		45	305	360	1400	0.09	0.67	0.12	0.39	0.10	0.60	0.03	0.19
Drain		34	138	283	1480	0.06	0.47	0.10	0.60	0.10	0.60	0.04	0.23
EFA	24												
Top lysimeter		116	540	706	1300	0.05	0.22	0.21	0.70	0.11	0.30	0.06	0.30
Middle lysimeter		123	775	588	1500	0.08	0.30	0.27	1.10	0.16	0.50	0.04	0.30
Bottom lysimeter		109	417	623	1500	0.09	0.35	0.24	0.80	0.13	0.50	0.04	0.20
Drain		79	246	686	2150	0.07	0.20	0.27	2.00	0.16	0.70	0.05	0.15
ESBM	24												
Top lysimeter		179	760	340	1100	0.13	0.55	0.47	3.00	0.21	0.70	0.06	0.17
Middle lysimeter		104	350	560	5600	0.13	0.45	0.38	2.10	0.20	0.80	0.06	0.32
Bottom lysimeter		95	390	324	3600	0.11	0.40	0.37	2.60	0.15	0.70	0.05	0.28
Drain		107	432	240	1700	0.15	0.85	0.30	1.40	0.18	0.80	0.06	0.20

[a] See Table 6 for residue identification.

TABLE 49. VARIATION IN OCEAN COLUMN LEACHATE CONSTITUENTS

Residue[a] Type	Number of Analyses	Range of Concentration (mg/l)											
		Cl^-		$SO_4^=$		Fe		Ni		Pb		Zn	
		avg	max	avg	max	avg	max	avg	max	avg	max	avg	max
NJFA	32												
Top lysimeter				3690	7520	1.22	7.16	2.56	6.80	0.69	1.70	0.35	1.95
Drain				3288	8610	0.67	2.90	2.00	6.00	0.61	1.60	0.17	0.82
NJSBM	42												
Top lysimeter				1708	3200	0.70	2.79	1.69	3.65	0.52	1.90	0.28	1.16
Drain				2065	4200	0.76	3.11	1.86	3.88	0.56	1.90	0.11	0.30
VFA	32												
Top lysimeter				3013	5400	0.71	0.10	1.98	8.00	0.50	1.50	0.29	2.31
Drain				3290	5500	0.68	2.69	1.89	6.00	0.56	1.60	0.15	0.39
VSBM	37												
Top lysimeter				1496	3500	0.86	6.50	1.38	3.40	0.82	2.80	0.42	1.85
Bottom lysimeter				1296	2380	0.89	3.50	1.32	1.32	0.76	2.50	0.22	0.70
Drain				1328	2400	0.89	4.80	1.45	4.04	0.77	2.40	0.15	0.33
EFA	22												
Top lysimeter				1367	2100	0.64	1.65	1.96	2.60	0.44	1.20	0.12	0.30
Drain				1393	2050	0.68	1.65	2.01	2.50	0.53	1.00	0.12	0.25
ESBM	24												
Top lysimeter				1621	3150	0.63	2.05	2.05	3.00	0.55	1.50	0.11	0.33
Drain				1657	2500	0.66	2.05	2.11	3.20	0.59	1.20	0.11	0.27

[a] See Table 6 for residue identification.

TABLE 50. VARIATION IN SANDY, CLAYEY, AND SILTY SOILS COLUMN LEACHATE CONSTITUENTS

Residue[a] Type	Number of Analyses	Range of Concentration (mg/l)											
		Cl^-		$SO_4^=$		Fe		Ni		Pb		Zn	
		avg	max	avg	max	avg	max	avg	max	avg	max	avg	max
Sandy Loam													
EFA	24												
Top lysimeter		111	290	369	1180	4.14	31.5	0.50	0.80	0.11	0.40	0.06	0.09
Middle lysimeter		96	251	192	1000	4.50	31.5	0.25	0.50	0.11	0.80	0.04	0.07
Bottom lysimeter		121	690	144	1050	12.93	37.0	0.24	0.60	0.07	0.30	0.03	0.06
Drain		128	446	293	1400	7.56	30.0	0.23	0.40	0.06	0.20	0.04	0.08
ESBM	24												
Top lysimeter		197	1120	495	1100	0.42	5.5	0.50	0.90	0.23	0.46	0.07	0.12
Middle lysimeter		191	625	479	2100	1.70	19.0	0.49	0.90	0.20	0.60	0.06	0.10
Bottom lysimeter		152	370	353	1600	1.85	22.0	0.43	1.10	0.15	0.70	0.07	0.24
Drain		140	591	177	1980	4.13	28.0	0.19	0.40	0.07	0.50	0.04	0.12
Clay Loam													
EFA	24												
Top lysimeter		114	500	953	3640	1.14	8.00	0.73	7.80	0.15	0.30	0.06	0.44
Middle lysimeter		123	528	1287	2300	1.64	5.70	0.67	7.60	0.12	0.30	0.05	0.15
Bottom lysimeter		129	840	920	2550	0.51	2.10	0.54	7.80	0.06	0.20	0.04	0.13
Drain		112	312	993	4050	1.25	2.55	0.59	8.80	0.10	0.39	0.06	0.46
ESBM	24												
Top lysimeter		223	929	976	4770	0.55	6.00	0.67	1.90	0.25	0.70	0.06	0.35
Middle lysimeter		274	776	1040	4500	0.24	0.50	0.59	1.90	0.25	0.70	0.06	0.26
Bottom lysimeter		178	500	1136	2720	0.52	1.85	0.40	0.80	0.17	0.60	0.04	0.08
Drain		208	1277	990	3675	0.48	1.65	0.29	0.50	0.12	0.60	0.05	0.12
Silty Loam													
EFA	24												
Top lysimeter		77	218	317	640	0.17	0.80	0.26	0.50	0.20	1.00	0.03	0.10
Middle lysimeter		64	208	469	900	0.14	0.30	0.27	0.40	0.14	0.50	0.02	0.04
Bottom lysimeter		121	730	379	920	0.18	0.85	0.26	0.50	0.13	0.30	0.03	0.05
Drain		97	470	663	1600	0.35	1.80	0.24	0.40	0.18	0.50	0.23	4.00
ESBM	24												
Top lysimeter		152	520	114	975	0.15	0.30	0.38	0.60	0.12	0.30	0.04	0.22
Middle lysimeter		176	825	100	681	0.12	0.25	0.31	0.50	0.13	0.40	0.03	0.09
Bottom lysimeter		193	640	57	210	0.11	0.20	0.31	0.60	0.18	0.90	0.03	0.06
Drain		155	579	62	300	0.09	0.20	0.19	0.60	0.08	0.30	0.02	0.04

[a] See Table 6 for residue identification.

volume was chosen to estimate real world rainfall data. Knowing the inside diameter of the columns,the 250 l volume of applied water was determined to be equivalent to 38.64 meter of precipitation. Assuming a specific real world annual precipitation of 76 cm and an 80 percent runoff coefficient,the 250 l applied rate was considered equivalent to a 50-year in-situ normal percolation condition for an average land surface.

Constituent Removal Through the Column Strata

The removal efficiency of the various simulated environments was calculated for each type of residue. The results are shown in Tables 51 to 56. The upper portion of each table lists the total weight of constituents contributed by the application of 250 l of potable water (or sea water for the ocean environment test columns). The total weight of the constituents in the residues are also listed.

Having established the total amount of constituents added to each test column, the percent removed from each stratum was next calculated. The weights of constituents contributed by the applied water and the quantity loss through the lysimeter ports were taken into consideration. The results are,therefore, representative of the quantity leached only from the residues.

The sanitary landfill column strata was the most effective environment for removing sulfate. The other environments generally were moderately,but less efficient, in attenuating sulfate. Most of the simulated environments were efficient in attenuating the heavy metals. The only exception was zinc,which readily leached through the limestone,dolomite,sanitary landfill,and the ocean (except the columns containing NJFA,VSBM,EFA,and ESBM columns. Zinc also readily leached through the soils columns containing ESBM. Fairly low percentages of lead removal were found in the ocean environment containing NJFA, the sanitary landfill test column containing EFA,and all but the soils simulated environments containing ESBM. The leachate collected from the sandy and clayey soil test columns contained high quantities of iron. The total quantities of iron in these latter bottom leachates were 10 to 30 times higher than the quantity found in the residues,due to high iron content in the natural soils. The silty soil test columns' drain leachates did not have excessive amounts of iron. In general,chlorides readily leached through the strata layers of the test columns. The only exceptions were the columns containing NJFA which retained moderate amounts of chloride. Overall,the sanitary landfill simulated environment showed the highest removal rate for NJFA,NJSBM,VSBM,and ESBM leachate constituents. The coal mine test column was the next best environment for removing the leached constituents from the fluidized-bed residues. For the disposal of the EFA,all the simulated environments,except the ocean test column showed overall high removal efficiencies.

Constituent Concentrations in the Test Columns' Drain Leachate

Figures 32 to 67 show the change in the concentration of the constituents found in the test column drain leachates with the quantity of water applied. These data include the results for the limestone and dolomite quarries,the sanitary landfill,and the coal mine

TABLE 51. CONSTITUENTS REMOVED BY THE TEST COLUMNS: NJFA

Source[a]	Total Weight of Constituent Applied to Column (g)					
	Cl^-	SO_4	Fe	Ni	Pb	Zn
Water (potable)	3,000	5,000	20	< 0.2	2	2
Sea Water (ocean columns)	--	675,000	525	175	750	55
Residue - NJFA	15,500	420,000	45	25	55	200

Environment and Layer	Percent of Constituent Removed from Each Strata Layer					
	Cl^-	$SO_4^=$	Fe	Ni	Pb	Zn
Limestone						
Environment	43	41	31	4	35	85
Claystone	15	0	16	0	14	1
Sandstone	5	0	15	68	11	2
Total removed	63	41	62	72	60	88
Dolomite						
Environment	61	31	4	60	29	83
Claystone	0	0	3	0	9	6
Sandstone	0	5	37	19	2	0
Total removed	61	36	42	79	40	89
Sanitary landfill						
Environment	1	74	--	72	9	4
Claystone	26	2	--	4	0	33
Sandstone	15	0	--	4	31	42
Granite	0	10	--	0	17	2
Total removed	42	86	--	80	57	81
Coal (bituminous)						
Environment	37	42	18	4	16	85
Claystone	0	6	0	0	2	4
Limestone	23	0	56	87	22	1
Sandstone	0	3	0	0	0	1
Total removed	60	51	74	93	40	91
Ocean						
Sandstone (upper)	--	10	4	28	31	24
Sandstone (lower)	--	21	54	38	2	11
Total removed	--	31	58	66	33	35

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[a] All quantities of water and percentage values were based on the addition of 250 l of water to the test columns.

TABLE 52. CONSTITUENTS REMOVED BY THE TEST COLUMNS: NJSBM

Source[a]	Total Weight of Constituent Applied to Column (g)					
	Cl^-	$SO_4^=$	Fe	Ni	Pb	Zn
Water (potable)	3,000	5,000	20	< 0.2	2	2
Sea Water (ocean columns)	--	675,000	525	175	750	55
Residue - NJSBM	11,000	350,000	30	20	55	710

Environment and Layer	Percent of Constituent Removed from Each Strata Layer					
	Cl^-	$SO_4^=$	Fe	Ni	Pb	Zn
Limestone						
Environment	30	58	50	10	4	95
Claystone	2	5	5	6	40	1
Sandstone	0	0	25	57	5	1
Total removed	32	63	80	73	49	97
Dolomite						
Environment	36	35	7	30	25	89
Claystone	0	21	50	29	18	5
Sandstone	0	8	6	6	11	0
Total removed	36	64	63	65	54	94
Sanitary landfill						
Environment	4	94	--	60	33	92
Claystone	12	3	--	15	2	0
Sandstone	15	0	--	0	9	5
Granite	4	0	--	10	6	1
Total removed	35	97	--	85	50	98
Coal (bituminous)						
Environment	43	47	53	5	22	0
Claystone	5	5	0	0	8	0
Limestone	0	8	14	88	0	99
Sandstone	0	5	0	0	3	0
Total removed	48	65	67	93	33	99
Ocean						
Sandstone (upper)	--	68	53	40	67	80
Sandstone (lower)	--	3	0	53	0	0
Total removed	--	71	53	93	67	80

[a] All quantities of water and percentage values were based on the addition of 250 l of water to the test columns.

TABLE 53. CONSTITUENTS REMOVED BY THE TEST COLUMNS: VFA

Source[a]	Total Weight of Constituent Applied to Column (g)					
	Cl^-	SO_4	Fe	Ni	Pb	Zn
Water (potable)	3,000	5,000	20	<0.2	2	2
Sea Water (ocean columns)	--	675,000	525	175	750	55
Residue - VFA	9,500	275,000	50	65	115	150

Environment and Layer	Percent of Constituent Removed from Each Strata Layer					
	Cl^-	$SO_4^=$	Fe	Ni	Pb	Zn
Limestone						
Environment	1	24	52	86	58	79
Claystone	34	10	4	3	5	5
Sandstone	18	2	0	2	17	0
Total removed	53	36	56	91	80	84
Dolomite						
Environment	2	36	8	80	58	87
Claystone	10	1	13	0	5	1
Sandstone	22	3	23	2	7	0
Total removed	34	40	44	82	70	88
Sanitary landfill						
Environment	11	89	--	92	70	86
Claystone	21	1	--	0	5	3
Sandstone	7	4	--	0	0	0
Granite	16	0	--	2	9	0
Total removed	55	94	--	94	84	89
Coal (bituminous)						
Environment	42	27	42	5	3	74
Claystone	0	0	0	0	16	0
Limestone	24	9	18	85	20	12
Sandstone	0	7	4	0	0	0
Total removed	66	43	64	90	35	86
Ocean						
Sandstone(upper)	--	28	64	46	70	73
Sandstone (lower)	--	0	0	36	0	0
Total removed	--	28	64	82	70	72

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[a] All quantities of water and percentage values were base on the addition of 250 l of water to test columns.

TABLE 54 . CONSTITUENTS REMOVED BY THE TEST COLUMNS: VSBM

Source[a]	Total Weight of Constituent Applied to Column (g)					
	Cl^-	SO_4	Fe	Ni	Pb	Zn
Water (potable)	3,000	5,000	20	<0.2	2	2
Sea Water (ocean columns)	--	675,000	525	175	750	55
Residue - VSBM	9,500	400	50	30	70	150

Environment and Layer	Percent of Constituent Removed from Each Strata Layer					
	Cl^-	$SO_4^=$	Fe	Ni	Pb	Zn
Limestone						
Environment	24	41	16	87	10	11
Claystone	15	7	35	7	22	42
Sandstone	8	3	11	3	23	14
Total removed	47	51	62	97	55	67
Dolomite						
Environment	26	46	6	70	44	47
Claystone	16	3	45	11	0	9
Sandstone	0	4	19	0	21	0
Total removed	42	53	70	81	65	56
Sanitary landfill						
Environment	8	62	--	3	28	42
Claystone	18	0	--	0	0	27
Sandstone	10	7	--	92	18	0
Granite	0	9	--	3	20	12
Total removed	34	78	--	98	66	81
Coal (bituminous)						
Environment	1	41	78	57	34	50
Claystone	13	11	0	3	0	16
Limestone	0	0	6	37	21	7
Sandstone	0	2	14	0	0	2
Total removed	14	54	98	97	55	75
Ocean						
Sandstone (upper)	--	63	40	67	59	0
Sandstone (middle)	--	5	14	25	5	14
Sandstone (lower)	--	0	0	0	0	36
Total removed	--	68	54	92	64	50

[a] All quantities of water and percentage values were base on the addition of 250 l of water to the test columns.

TABLE 55. CONSTITUENTS REMOVED BY THE TEST COLUMNS: EFA

Source[a]	Total Weight of Constituent Applied to Column (g)					
	Cl^-	$SO_4^=$	Fe	Ni	Pb	Zn
Water (potable)	3,000	5,000	20	< 0.2	2	2
Sea Water (ocean columns)	--	675,000	525	175	750	55
Residue – EFA	150,000	320,000	70	200	100	80

Environment and Layer	Percent of Constituent Removed from Each Strata Layer					
	Cl^-	$SO_4^=$	Fe	Ni	Pb	Zn
Limestone						
Environment	74	26	91	94	36	61
Claystone	0	39	0	0	0	0
Sandstone	8	0	0	0	15	4
Total removed	81	65	91	94	51	65
Dolomite						
Environment	5	38	79	96	53	90
Claystone	23	22	0	0	0	0
Sandstone	11	0	0	0	14	0
Total removed	39	60	79	96	67	90
Sanitary landfill						
Environment	75	58	--	94	7	76
Claystone	0	0	--	0	0	4
Sandstone	10	0	--	0	14	9
Granite	0	0	--	2	0	0
Total removed	85	58	--	96	21	89
Coal (bituminous)						
Environment	72	35	87	96	45	65
Claystone	0	18	0	0	0	0
Limestone	6	0	0	1	1	12
Sandstone	2	0	3	0	0	0
Total removed	80	53	90	97	46	77
Ocean						
Sandstone (upper)	--	65	70	92	32	4
Sandstone (lower)	--	0	0	0	2	0
Total removed	--	65	70	92	34	4

(Continued)

TABLE 55 (Cont.)

Source[a]	Total Weight of Constituent Applied to Column (g)					
	Cl^-	$SO_4^=$	Fe	Ni	Pb	Zn
Water (potable)	3,000	5,000	20	< 0.2	2	2
Sea Water (ocean columns)	--	675,000	525	175	750	55
Residue - EFA	75,000	375,000	70	200	100	80

Environment and Layer	Percent of Constituent Removed from Each Strata Layer					
	Cl^-	$SO_4^=$	Fe	Ni	Pb	Zn
Sandy loam						
Top	85	69	--[c]	96	13	75
Middle, upper	1	8	--	1	46	4
Middle, lower	0	4	--	1	1	5
Bottom	0	0	--	0	0	0
Total removed	86	81	--	98	60	84
Clayey loam[b]						
Top	91	51	--[c]	98	37	71
Middle upper	0	0	--	0	11	4
Middle lower	< 1	11	--	0	13	7
Bottom	< 1	0	--	0	0	0
Total removed	91	62	--	98	61	82
Silty loam						
Top	85	69	44	98	26	38
Middle, upper	4	0	11	0	0	27
Middle, lower	0	2	0	0	6	0
Bottom	< 1	0	0	0	7	0
Total removed	89	71	55	98	39	65

[a] All quantities of water and percentage values were based on the addition of 250 l of water to the test columns.

[b] Total volume applied to column was 170 l, resulting from reduced permeability.

[c] Very high concentrations of iron were found, not representative of actual removal efficiency.

TABLE 56. CONSTITUENTS REMOVED BY THE TEST COLUMNS; ESBM

Source[a]	Total Weight of Constituent Applied to Column (g)					
	Cl^-	SO_4.	Fe	Ni	Pb	Zn
Water (potable)	3,000	5,000	20	0.2	2	2
Sea Water (ocean columns)	--	675,000	525	175	750	55
Residue - ESBM	75,000	375,000	50	345	200	125

Environment and Layer	Percent of Constituent Removed from Each Strata Layer					
	Cl^-	$SO_4^=$	Fe	Ni	Pb	Zn
Limestone						
Environment	49	50	64	96	39	44
Claystone	0	7	0	0	0	0
Sandstone	0	0	0	1	0	0
Total removed	45	57	64	97	39	44
Dolomite						
Environment	0	65	64	93	36	55
Claystone	12	0	0	0	0	0
Sandstone	36	3	1	0	0	0
Total removed	48	68	65	93	36	55
Sanitary landfill						
Environment	36	89	--	92	45	59
Claystone	15	0	--	0	0	0
Sandstone	0	0	--	1	0	0
Granite	0	0	--	1	0	3
Total removed	51	89	--	94	45	62
Coal (bituminous)						
Environment	4	28	56	95	8	45
Claystone	52	0	0	0	16	3
Limestone	4	24	6	0	2	7
Sandstone	0	2	0	0	9	0
Total removed	60	54	62	95	35	55
Ocean						
Sandstone (upper)	--	61	66	94	34	11
Sandstone (lower)	--	0	0	0	0	0
Total removed	--	61	66	94	34	11

(Continued)

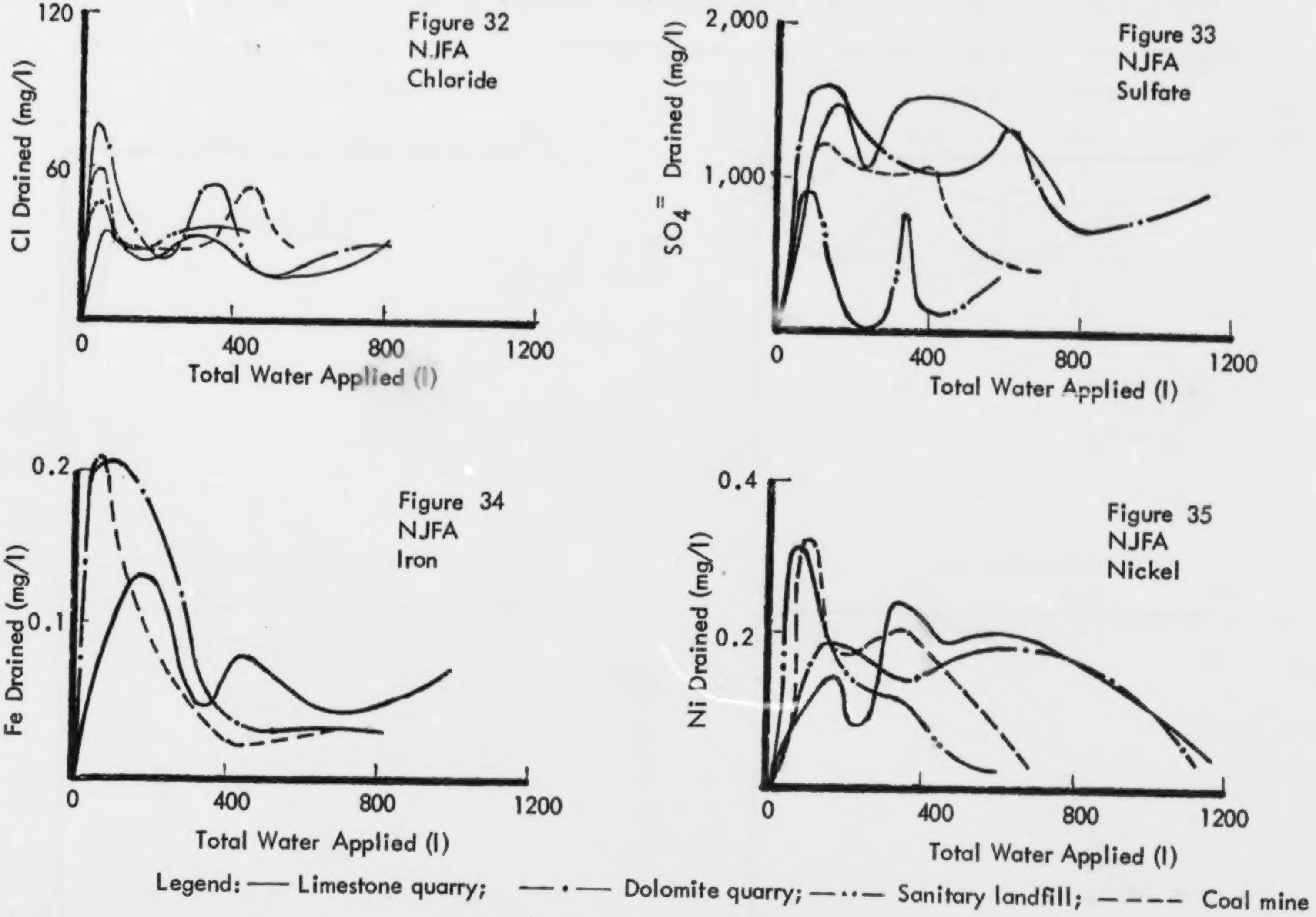
TABLE 56 (Cont.)

Source[a]	Total Weight of Constituent Applied to Column (g)					
	Cl^-	$SO_4^=$	Fe	Ni	Pb	Zn
Water (potable)	3,000	5,000	20	0.2	2	2
Sea Water (ocean columns)	--	--	--	--	--	--
Residue - ESBM	75,000	375,000	50	345	200	125

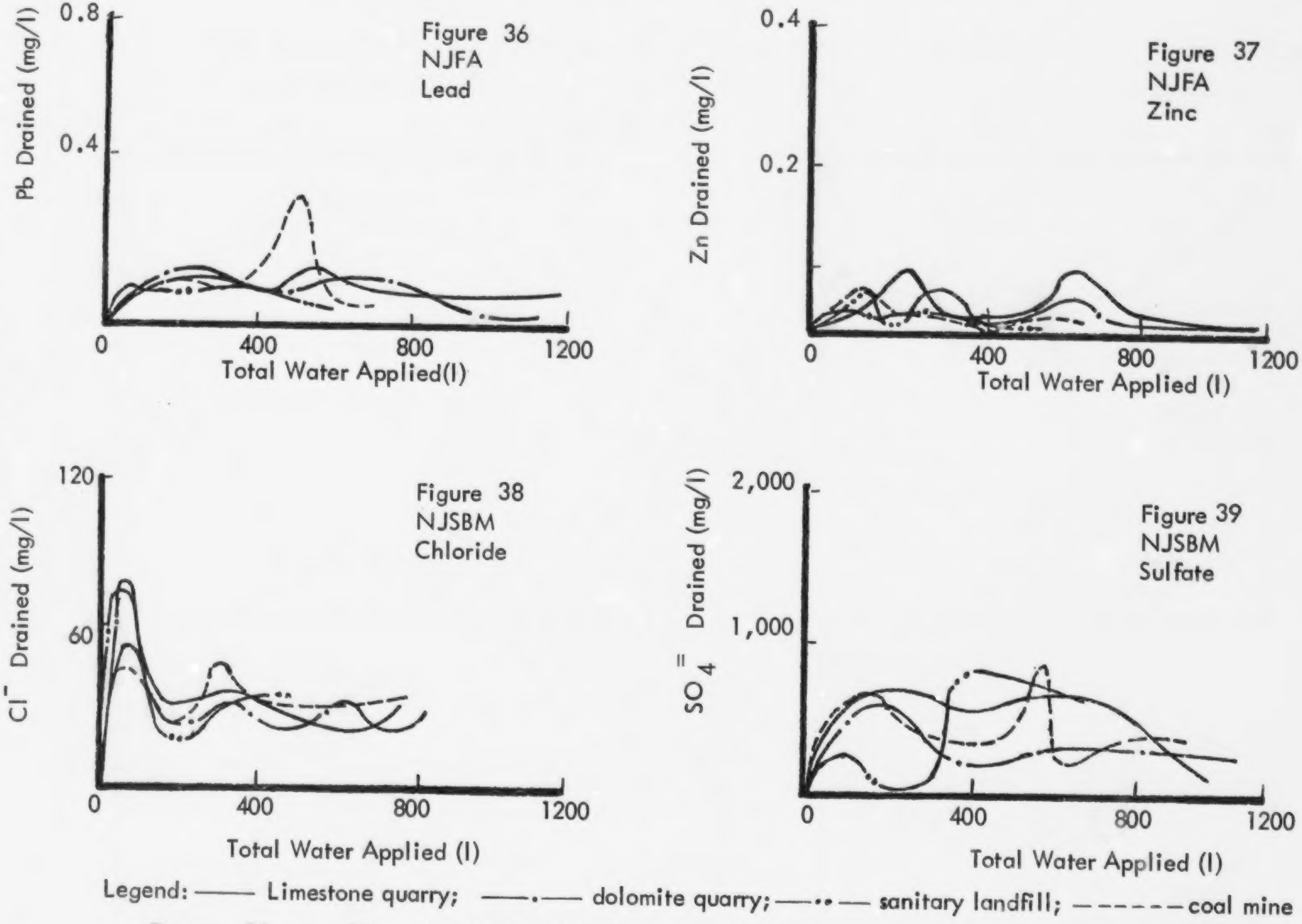
Environment and Layer	Percent of Constituent Removed from Each Strata Layer					
	Cl^-	$SO_4^=$	Fe	Ni	Pb	Zn
Sandy loam						
Top	36	67	--[b]	94	24	52
Middle, upper	0	1	--	1	7	4
Middle, lower	12	7	--	0	8	14
Bottom	7	8	--	1	26	9
Total removed	55	83	--	96	65	79
Clayey loam						
Top	44	53	--[b]	96	27	59
Middle, upper	0	0	--	0	8	1
Middle, lower	35	0	--	1	15	7
Bottom	0	7	--	0	5	3
Total removed	79	60	--	97	55	70
Silty loam						
Top	54	93	53	98	50	83
Middle, upper	0	4	0	0	4	0
Middle, lower	0	<1	0	0	0	0
Bottom	0	0	0	0	3	1
Total removed	54	97	53	98	57	84

[a] All quantities of water and percentage values were based on the addition of 250 l of water to the test columns.

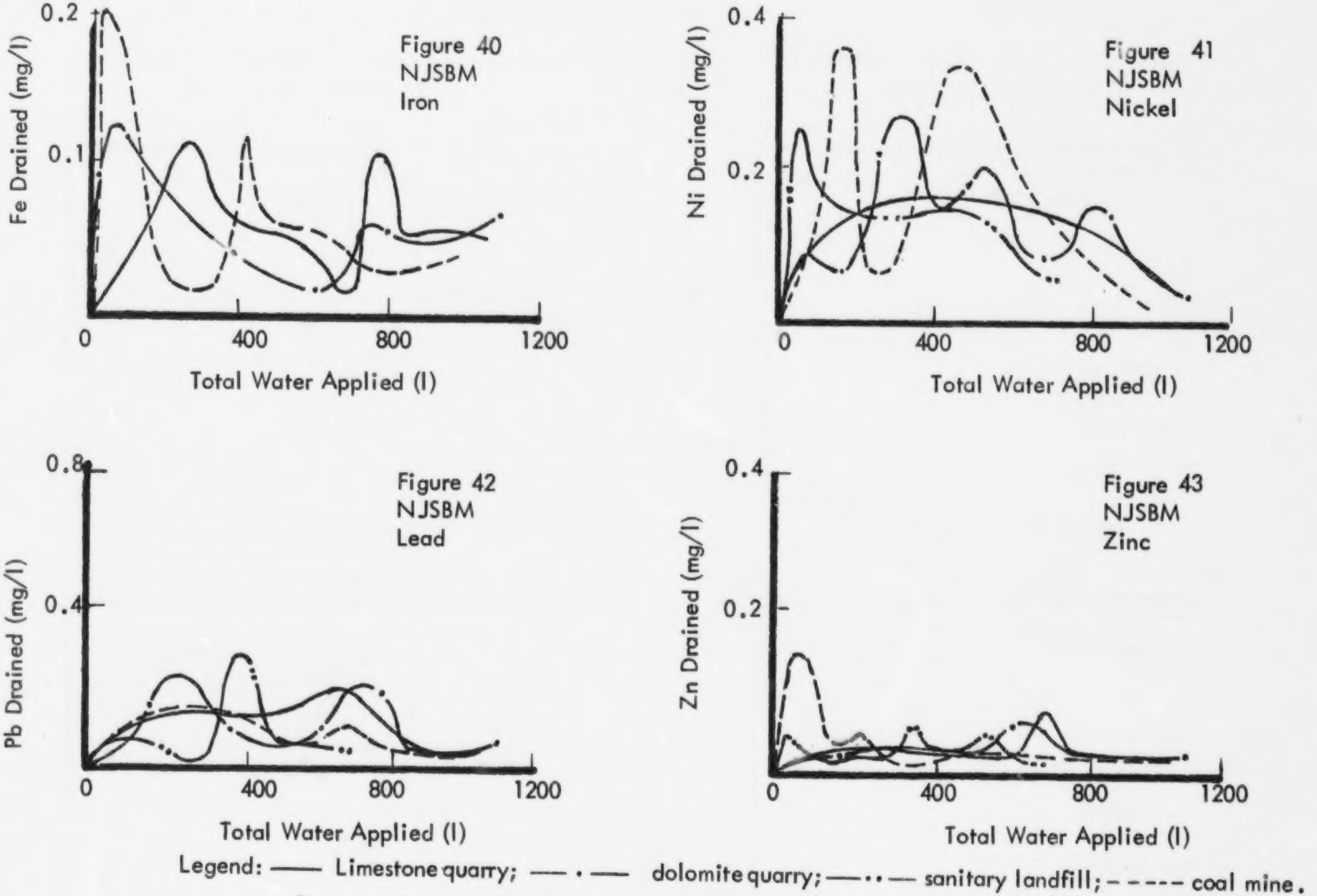
[b] Very high concentrations of iron were found, not representative of actual removal efficiency.



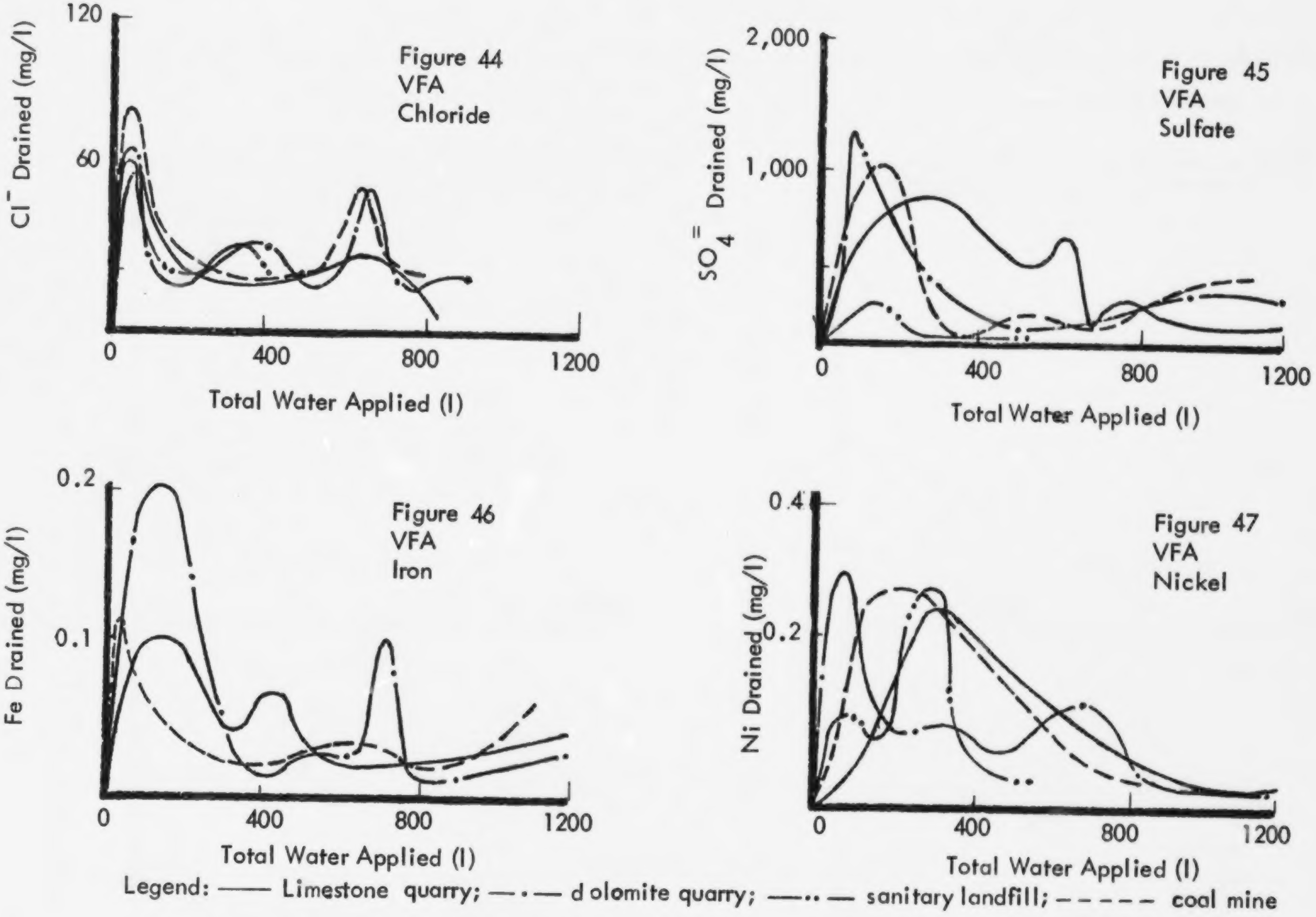
Figures 32 to 35 . Chloride, sulfate, iron, and nickel leached from test columns: NJFA.



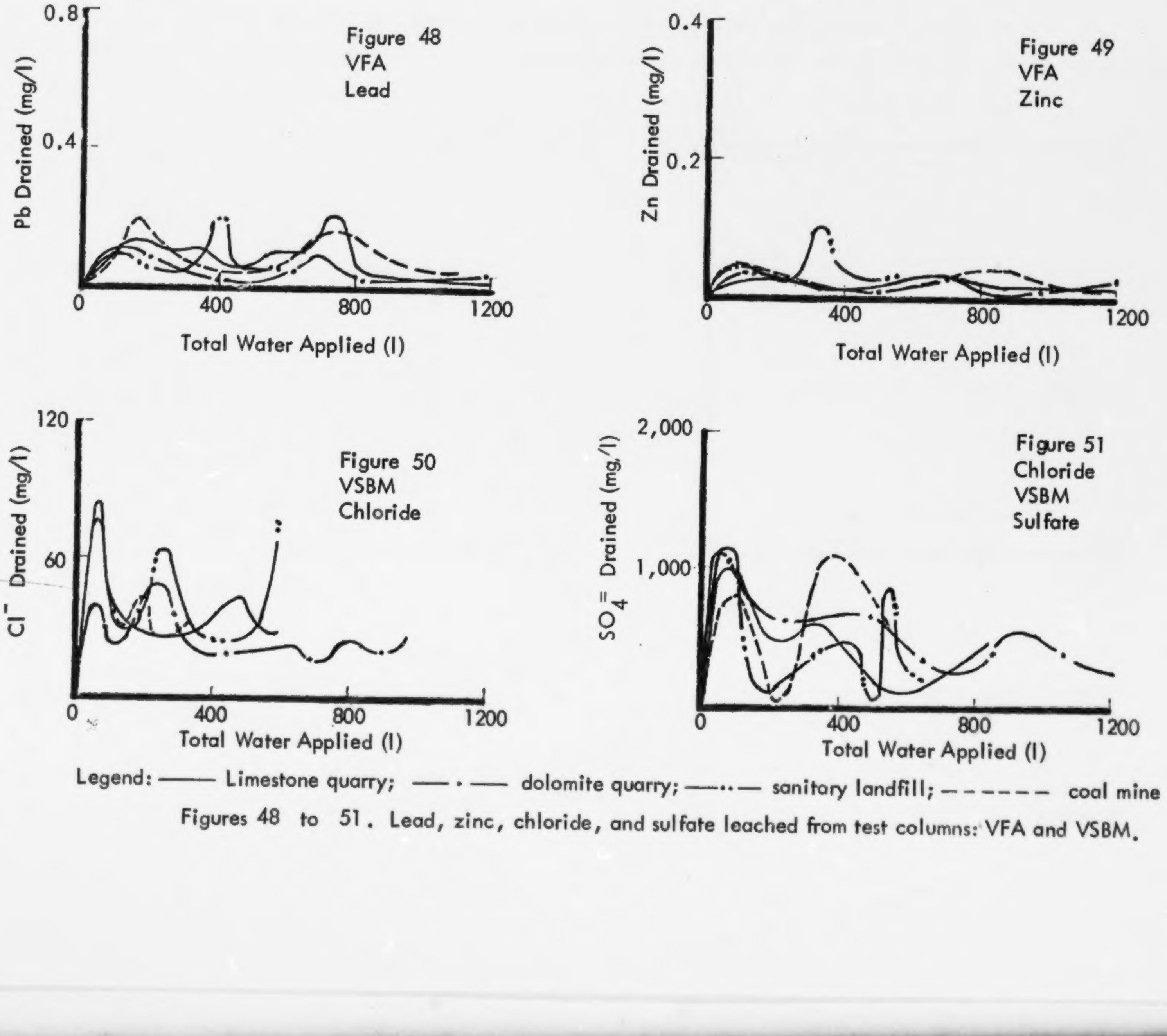
Figures 36 to 39 . Lead, zinc, chloride and sulfate leached from test columns: NJFA and NJSBM.



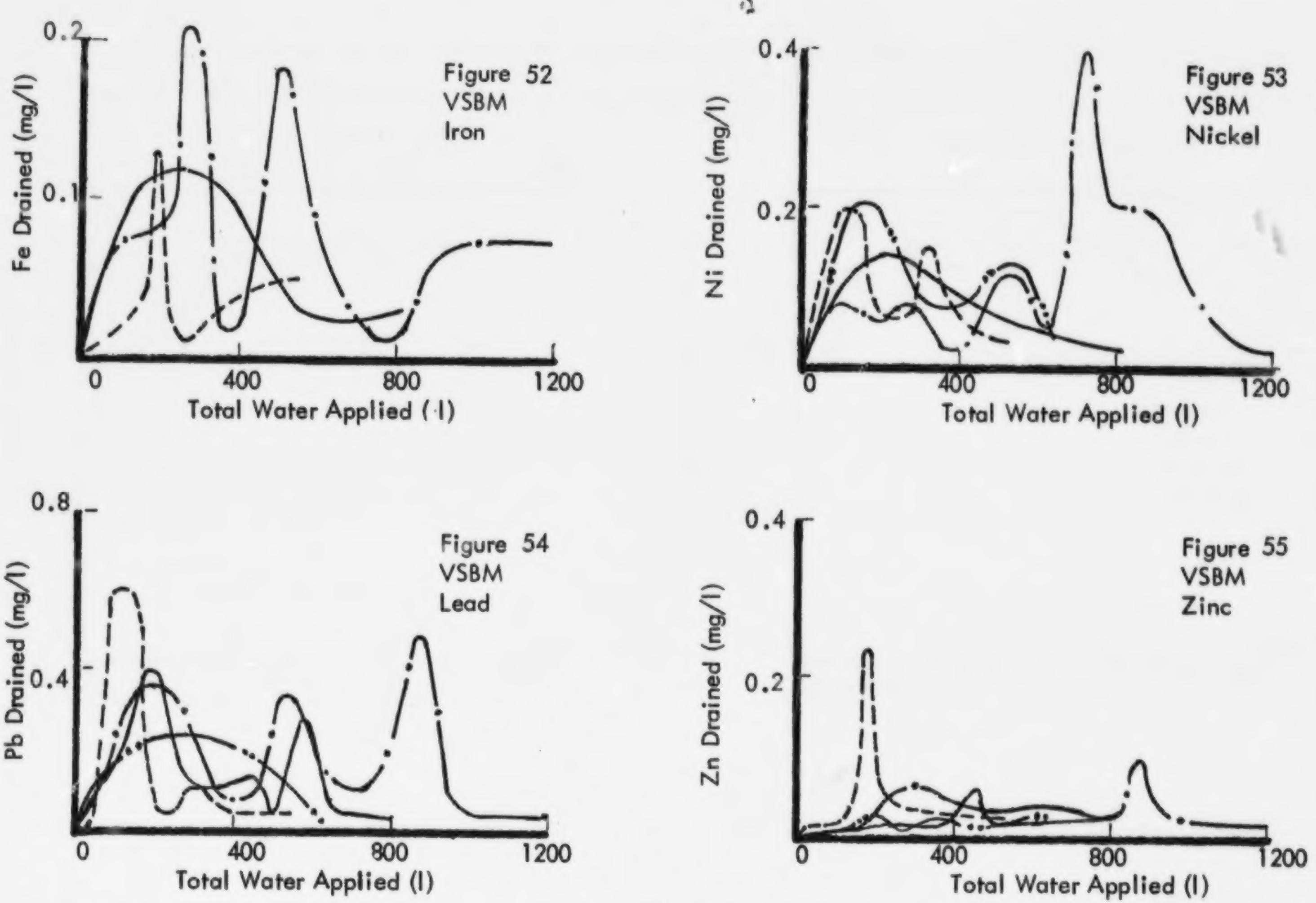
Figures 40 to 43 . Iron, nickel, lead, and zinc leached from test columns: NJSBM.



Figures 44 to 47 . Chloride, sulfate, iron, and nickel leached from test columns: VFA.

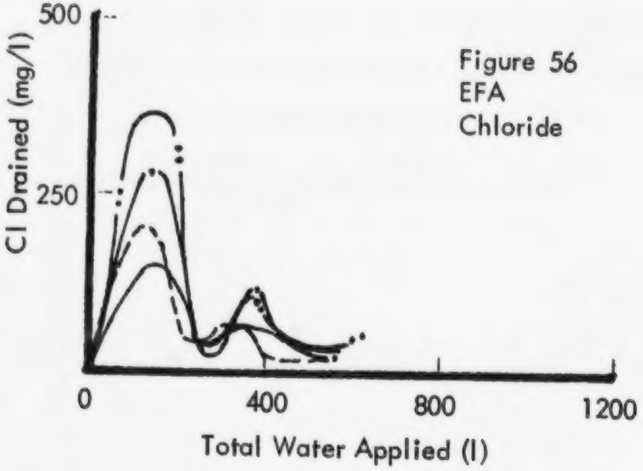


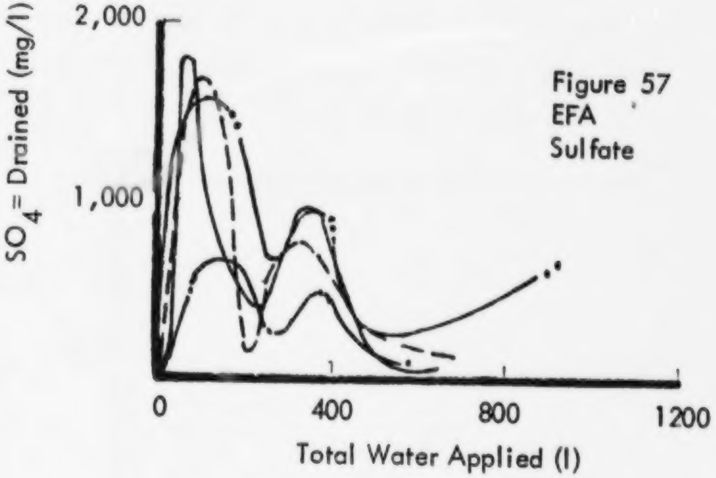
Figures 48 to 51. Lead, zinc, chloride, and sulfate leached from test columns: VFA and VSBM.

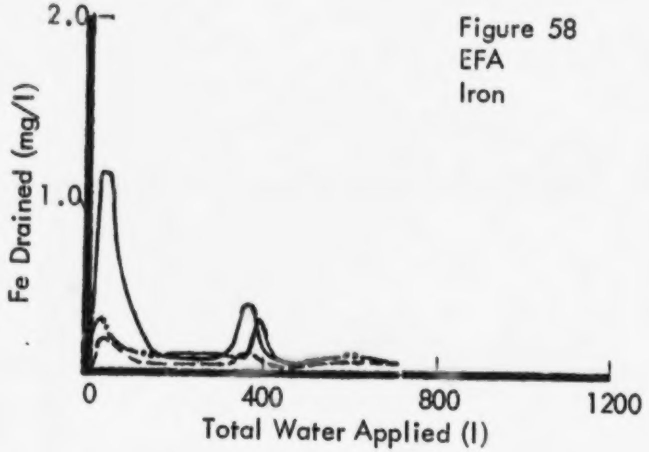


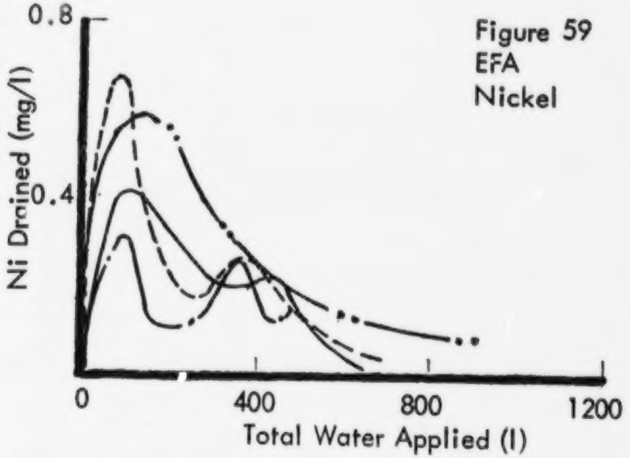
Legend: —— Limestone quarry; —— • —— dolomite quarry; —— • • —— sanitary landfill; – – – – – coal mine

Figures 52 to 55. Iron, nickel, lead, and zinc leached from test columns: VSBM.



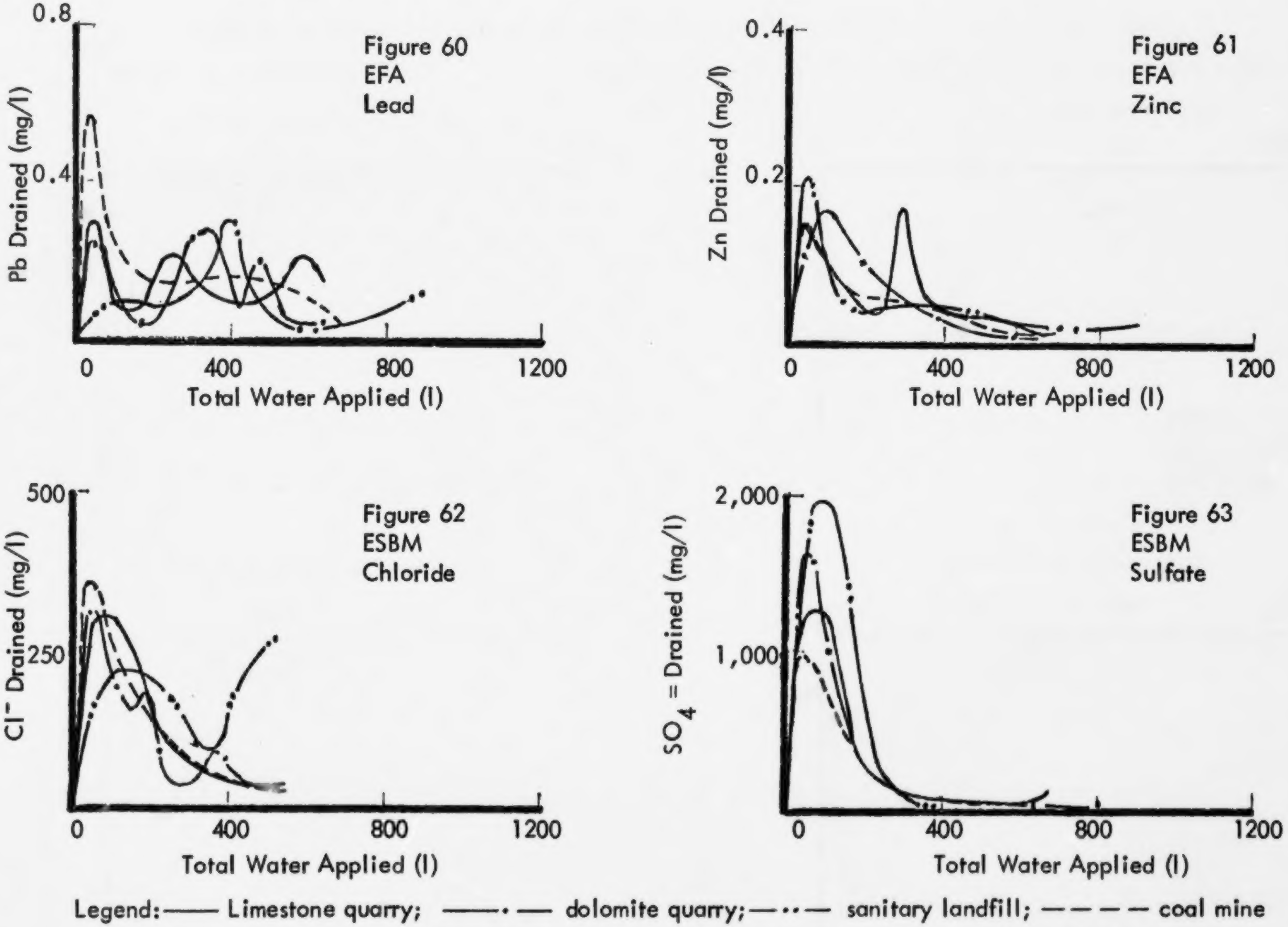




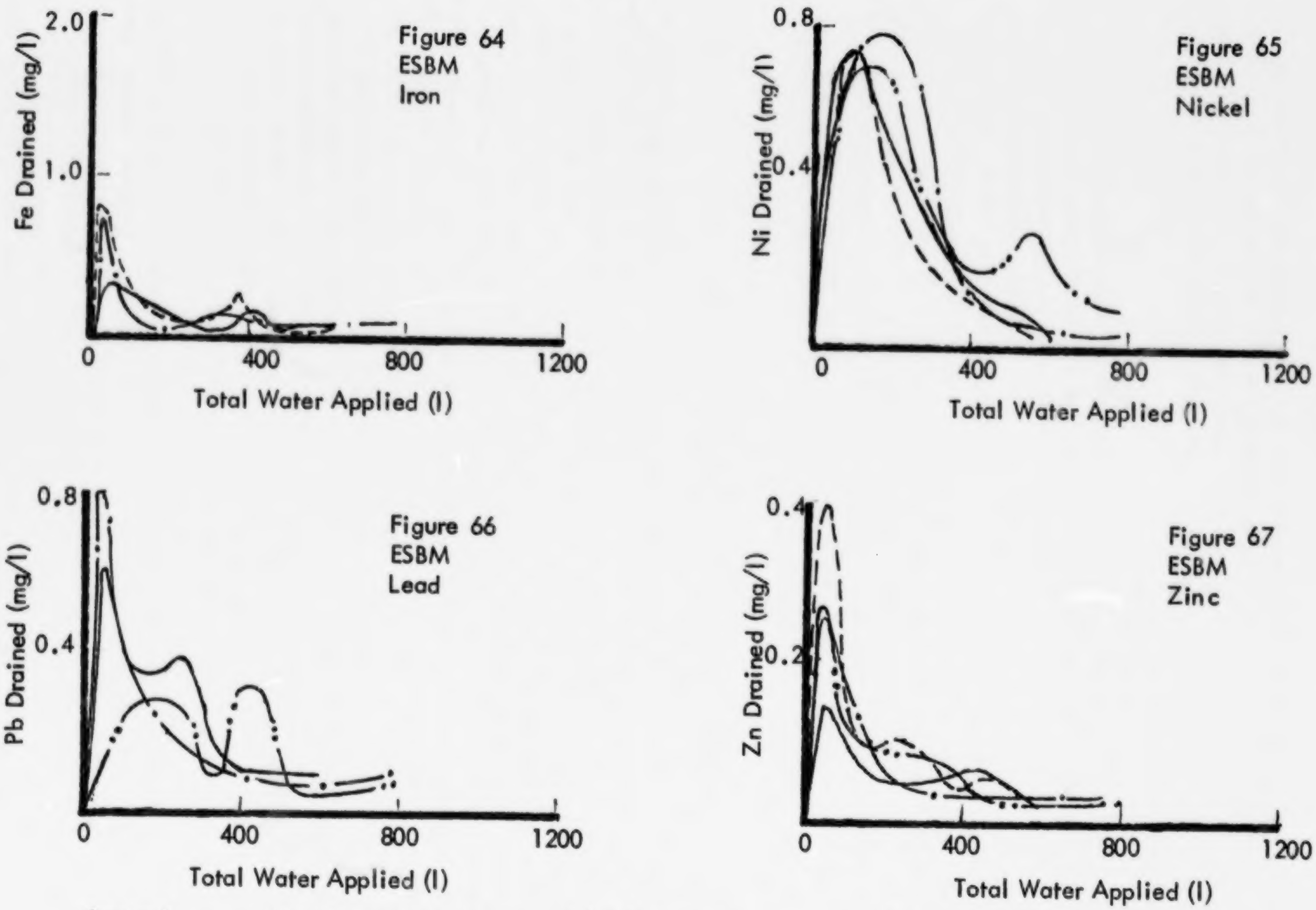


Legend: —— Limestone quarry; —·— dolomite quarry; —··— sanitary landfill; - - - - coal mine

Figures 56 to 59 . Chloride, sulfate, iron, and nickel leached from test columns: EFA.



Figures 60 to 63 . Lead, zinc, chloride, and sulfate leached from test columns: EFA and ESBM.



Legnnd: ——— Limestone quarry; —·— dolomite quarry; —·· —sanitary landfill; – – – – – – coal mine

Figures 64 to 67 . Iron,nickel,lead,and zinc leached from test columns: ESBM.

environments. The ocean test column results were not plotted because the leachate contained a high percentage of constituents attributed to the natural sea water applied; therefore, the impact of the residue, alone, could not be determined. The results for the soil loam simulated environments were also not plotted because similar behavior was found for all the constituents.

For nearly all the test columns' environments, chlorides, sulfates, iron, and nickel were readily leached during the first 50 to 100 l (equivalent to 7 to 14 meters of assumed rainfall) of applied water infiltrations. This can be readily seen by the peak concentrations as shown in the plots. Broad peaks, indicative of major leaching, were seen for the sulfate and iron constituents leached from the NJFA, NJSBM, VFA and VSBM. Broad peak concentrations also occurred for chloride and nickel constituents leached from the Esso residues. Fairly constant leaching of lead and zinc occurred throughout the test period as shown by the small peaks and valleys plotted in the figures. For the NJFA, NJSBM, VFA, and VSBM leachates, the sanitary landfill and the coal mine simulated environments generally had lower concentrations of constituents than the other test column leachates. The dolomite quarry test column leachates generally contained less constituents in the EFA and ESBM leachates.

Comparison of Constituents Leached with Surface Water Criteria

Table 57 lists the 1975 Environmental Protection Agency interim drinking water regulations and the surface water criteria for public water supplies as mandated in the California Administrative Codes. Table 58 lists the recommended maximum concentrations of trace elements in irrigation water. The leachate analyses were compared with these surface and drinking water criteria to determine the possible impact of the residues on groundwater quality. The results are shown in Tables 59 to 63. The quality of water applied to the columns and leached past the lysimeters were used to calculate the percentages for which each constituent exceeded the noted water quality criteria. The summation of the quantity of water associated with each composite sample, for which the water quality criteria was exceeded, was divided by the total quantity of water applied to the column or passing by the lysimeter (as listed in Tables 59 to 63). Each fraction was multiplied by 100 to convert it to a percent. As noted earlier in this chapter 50 l of applied water to each column was considered to be equivalent to 7 meters of in-situ percolation condition for an assigned average rainfall land surface. Therefore, the percentage values as shown in Tables 59 to 63 relate to the percent of leachate volume expected to be generated at such a site which would exceed the noted water quality criteria.

Chloride concentrations did not exceed the water quality criteria in any environment on which the Exxon, New Jersey and the Pope, Evans, and Robbins, Virginia residues were added. From 3 to 30 percent of the leachate from the EFA and ESBM exceeded the chloride water criteria; the residues from the Esso pilot plant, Great Britain, contained nearly ten times the quantity of chlorides as did the United States-processed residues (see Table 16, Chapter 5). For most of the simulated environments, 50 to 90 percent of the leachate volume exceeded the sulfate water quality criteria. The notable exceptions

TABLE 57 . EPA INTERIM PRIMARY DRINKING WATER REGULATIONS, 1975[1] AND WATER QUALITY CRITERIA FOR BENEFICIAL USES[2]

Constituent[b]	EPA Interim Primary Drinking Water Regulations Maximum Contaminant Level	Water Quality Criteria for Beneficial Supplies[a] Municipal	Agricultural	Industrial[c]	Recreational (1)	Recreational (2)	Aquatic Habitat[d]
Physical							
Color	--	15/-	--	--	15/100	15/100	--
Odor (number)	--	3/-	--	--	32/256	32/256	--
Temperature	--	--	--	--	30°C	30°C	5°F above nat.
Turbidity (JTU)	1[e]	5/-[f]	--	--	--	--	10 or 10% above natural[g]
Suspended Solids	--	--	--	5,000	20/100	20/100	--
Transparency (feet)	--	--	--	--	4	4	--
Inorganic Chemicals							
Total Alkalinity	--	--	--	--	--	--	20[h]
Aluminum	--	--	5/20	--	--	--	0.1
Arsenic	0.05	0.1	.1/2.0[i]	--	--	--	0.01
Ammonia (as N)	--	--	--	--	--	--	0.01
Barium	1.0	1.0	--	--	--	--	0.5
Berylium	--	.1/.5	--	--	--	--	--
Boron	--	1.0	0.5/2-10	--	--	--	--
Chloride	--	250/1,000	70/300-1,000	600	--	--	--
Chlorine[i]	--	--	--	--	--	--	0.003
Cadmium	--	0.01	.01/.05	--	--	--	0.003
Chromium	0.05	0.05	.10/1.0	--	--	--	0.05
Cobalt	--	--	.05/5.0	--	--	--	--
Carbon Dioxide	--	--	--	--	--	--	15[h]
Copper	--	1.0/-	.2/5.0	--	--	--	0.01
Cyanide	--	.01/0.2	--	--	--	--	0.005

Continued

TABLE 57 . (Continued)

Constituent[b]	EPA Interim Primary Drinking Water Regulations Maximum Contaminant Level	Water Quality Criteria for Beneficial Supplies[a]					
		Municipal	Agricultural	Industrial[c]	Recreational (1)	Recreational (2)	Aquatic Habitat[d]
Inorganic Chemicals (Cont.)							
Fluoride	1.4-2.4[j]	0.8-1.7	1.0/15.0[k]	--	--	--	1.5
$CaCO_3$	--	500/-	--	850	--	--	--
Iron	--	0.3	5.0/20.0	--	--	--	0.5
Lead	0.05	0.05	5.0/10.0	--	--	--	0.01
Lithium	--	--	2.5	--	--	--	--
Manganese	--	0.05/-	0.2/10.0	--	--	--	0.02
Mercury	0.005	0.005	--	--	--	--	0.001
Molybdenum	--	--	0.01/0.05	--	--	--	--
Nickel	--	--	0.2/2.0	--	--	--	0.002
$NO_3 + NO_2$ (as N)	10	10	--	--	--	--	--
pH (units)	--	6.0-8.5	5.5-8.3/ 4.5-9.0	--	6.5-8.3/ 6.0-9.0	6.5-8.3 6.0-9.0	6.5-8.5[l]
Selenium	0.01	0.01	0.02	--	--	--	0.005
Silver	0.05	0.05	--	--	--	--	0.001
Sodium Absorption Ratio (SAR)	--	--	4.0/10-20	--	--	--	--
Sulfate	--	250-500	--	680	--	--	--
Sulfite	--	--	--	--	--	--	0.002
TDS	--	500/1,500	--	1,000	--	--	1,500[g]
EC (umhos/cm)	--	--	--	--	--	--	3,000[h]
Uranyl ion	--	5	--	--	--	--	--
Vanadium	--	--	0.10/1.0	--	--	--	--
Zinc	--	5/-	2.0/10.0	--	--	--	0.02

Continued

TABLE 57 (Continued)

	EPA Interim Primary Drinking Water Regulations Maximum Contaminant Level	Water Quality Criteria for Beneficial Supplies[a]					
		Municipal	Agricultural	Industrial	Recreational (1)	Recreational (2)	Aquatic Habitat
Organic Chemical							
MBAS	--	0.05/0.5	--	--	1.0-2.0	1.0-2.0	--
Oil and grease	--	--	--	--	0/5.0	0/5.0	0
Phenols	--	0.001/-	--	--	--	--	0.01
PCB's	--	--	--	--	--	--	0.0001
Phthalate esters	--	--	--	--	--	--	0.3
Chlorinated hydrocarbons							
Endrin	0.0002	--	--	--	--	--	--
Lindane	0.004	--	--	--	--	--	--
Methoxychlor	0.1	--	--	--	--	--	--
Toxaphene	0.005	--	--	--	--	--	--
Chlorophenoxys							
2,4-D	0.1	--	--	--	--	--	--
2,4,5-TD silvex	0.01	--	--	--	--	--	--
ABS	--		--	--	--	--	1.0
Carbon alcohol extract	--	3	--	--	--	--	--
Carbon chloroform extract	--	-- 0.15	--	--	--	--	--
COD	--	--	--	75	--	--	--
LAS	--	--	--	--	--	--	0.2
Biological Properties							
Total coliform (per 100 ml)	1[p]	100/10,000	5,000/-	--	--	--	1,000[k]
Fecal coliform (per 100 ml)	--	20/2,000	1,000/-	--	200	2,000	--
Dissolved oxygen	--	--	--	--	--	--	90% of natural
Toxicity[q]	--	--	--	--	--	--	1.0

Continued

TABLE 57 (Continued)

Constituent[b]	EPA Interim Primary Drinking Water Regulations Maximum Contaminant Level	Water Quality Criteria for Beneficial Supplies[a] Municipal	Agricultural	Industrial	Recreational (1)	Recreational (2)	Aquatic Habitat
Radioactivity							
Gross beta (pc/1)	--	1,000	1,000	--	--	--	100-1,000
Radium 226 (pc/1)	--	3	3	--	--	--	1-3
Strontium 90 (pc/1)	--	10	10	--	--	--	2-10

[a] Where two values appear (e.g., a/b), the first number represents a threshold concentration, and the second represents a limiting concentration. All single numbers represent limiting concentrations. Limiting concentrations are suggested as 90 percentile limits, not to be violated by controlling factors more than 10 percent of the time.

[b] Values are in terms of mg/l unless otherwise noted.

[c] Cooling water requirements for fresh water once through.

[d] Includes COMM, WARM, COLD, BIOL, SAL, WILD, RARE, MAR, MIGR, SPWN, except where otherwise noted.

[e] Monthly average, 5TU for an average of the consecutive days.

[f] As measured by Secchi disc or expressed as percent light transmittance at prescribed depth.

[g] Applicable only as 10 percent above background for COMM, BIOL, SAL, and MAR.

[h] Applicable only to fresh waters; e.g., WARM, COLD, WILD, RARE, MIGR, SPWN.

[i] Residual chlorine.

[j] Dependent on temperature from below 12° C to 32.5° C; higher limits for lower temperatures.

[k] Concentrations for water used by livestock are more stringent. They are: arsenic 0.05/1.0 and fluoride 1.0/5.0.

[l] Applicable only to WARM, COLD, RARE, MIGR, and SPWN; COMM, BIOL, SAL, and MAR are 7.0-8.5 units pH; WILD is 7.0-.2 pH.

[m] Applicable only to WARM, COLD, RARE, and SPWN; WILD is 1%± natural per 24 hrs.

[n] Applicable only to COMM, BIOL, SAL, and MAR.

[p] Monthly average for the membrane filter technique.

[q] Based upon summation of ratios of concentrations of potential toxicants and permissible concentrations; values for COMM, BIOL, SAL, and MAR should not exceed 0.4.

Source: 162, 186.

TABLE 58 . RECOMMENDED MAXIMUM CONCENTRATIONS OF TRACE ELEMENTS IN IRRIGATION WATERS

Element	For Waters Used Continuously on All Soil mg/l	For Use up to 20 Years on Fine-Textured Soils of pH 6.0 to 8.5 mg/l
Aluminum	5.0	20.0
Arsenic	0.10	2.0
Beryllium	0.10	0.50
Boron	0.75	2.0-10.0
Cadmium	0.010	0.050
Chromium	0.10	1.0
Cobalt	0.050	5.0
Copper	0.20	5.0
Fluoride	1.0	15.0
Iron	5.0	20.0
Lead	5.0	10.0
Lithium	2.5[b]	2.5[b]
Manganese	0.20	10.0
Molybdenum	0.010	0.050[c]
Nickel	0.20	2.0
Selenium	0.020	0.020
Zinc	2.0	10.0

[a] These levels will normally not adversely affect plants or soils. No data are available for mercury, silver, tin, titanium, tungsten.

[b] Recommended maximum concentration for irrigating citrus is 0.075 mg/l.

[c] For only acid fine-textured soils or acid soils with relatively high iron oxide contents.

Source: 187.

TABLE 59. COMPARISON OF LIMESTONE COLUMN LEACHATE CONSTITUENTS WITH WATER QUALITY CRITERIA FOR MUNICIPAL WATER SUPPLIES[d]

Residue Type and Sample Point	Total Water (liters)	Percent Constituent Exceeded Water Quality Criteria[e]				
		Cl (250 mg/l)[a,b]	SO_4 (250 mg/l)[b]	Fe (0.3 mg/l)[b]	Pb (0.05 mg/l)[c]	Zn (5.0 mg/l)[b]
NJFA						
Top lysimeter	883	0	88	14	78	0
Bottom lysimeter	735	0	90	7	86	0
Drain	530	0	92	7	81	0
Average		0	90	10	81	0
NJSBM						
Top lysimeter	936	0	78	2	91	0
Bottom lysimeter	656	0	80	10	83	0
Drain	412	0	87	3	84	0
Average		0	82	5	86	0
VFA						
Top lysimeter	906	0	67	5	76	0
Bottom lysimeter	697	0	90	10	77	0
Drain	488	0	79	4	73	0
Average		0	78	6	75	0
VSBM						
Top lysimeter	659	0	81	22	79	0
Bottom lysimeter	482	0	69	14	58	0
Drain	319	0	64	7	63	0
Average		0	71	17	67	0
EFA						
Top lysimeter	593	8	96	0	70	0
Bottom lysimeter	478	4	81	3	81	0
Drain	382	0	86	8	88	0
Average		4	88	4	80	0
ESBM						
Top lysimeter	560	15	72	4	96	0
Bottom lysimeter	475	20	58	3	78	0
Drain	388	20	15	15	87	0
Average		18	48	8	88	0

[a] Permissible criteria for each constituent is given in parenthesis.

[b] Water quality criteria for municipal water supply.

[c] Maximum contaminant level for the EPA interim primary drinking water regulation, 1977.

[d] The leachate analyses and the volume of water applied during the last four months of the monitoring program were not included in the calculations because only the drain leachates were sampled and analyzed.

[e] The values include only the constituents leached from the residue. The quantities of metals and ions resulting from the applied water were not included in the calculations.

TABLE 60. COMPARISON OF DOLOMITE COLUMN LEACHATE CONSTITUENTS WITH WATER QUALITY CRITERIA FOR MUNICIPAL WATER SUPPLIES[d]

Residue Type and Sample Point	Total Water (liters)	Percent Constituent Exceeded Water Quality Criteria[e] Cl (250 mg/l)[a,b]	SO$_4$ (250 mg/l)[b]	Fe (0.3 mg/l)[b]	Pb (0.05 mg/l)[c]	Zn (5.0 mg/l)[b]
NJFA						
Top lysimeter	874	0	91	8	77	0
Bottom lysimeter	600	0	91	12	75	0
Drain	355	0	90	8	58	0
Average		0	91	9	70	0
NJSBM						
Top lysimeter	898	0	86	16	91	0
Bottom lysimeter	665	0	86	4	64	0
Drain	431	0	61	3	65	0
Average		0	78	8	73	0
VFA						
Top lysimeter	907	0	37	8	53	0
Bottom lysimeter	633	0	43	8	65	0
Drain	363	0	34	5	37	0
Average		0	38	7	52	0
VSBM						
Top lysimeter	1024	0	95	21	85	0
Bottom lysimeter	695	0	95	11	68	0
Drain	377	0	88	5	87	0
Average		0	93	12	80	0
EFA						
Top lysimeter	583	19	96	6	62	0
Bottom lysimeter	460	22	87	7	47	0
Drain	338	23	68	3	61	0
Average		21	84	6	57	0
ESBM						
Top lysimeter	545	17	26	4	62	0
Bottom lysimeter	415	18	18	4	69	0
Drain	285	29	16	12	80	0
Average		21	20	7	71	0

[a] Permissible criteria for each constituent is given in parentheses.

[b] Water quality criteria for municipal water supply.

[c] Maximum contaminant level for the EPA interim primary drinking water regulations, 1977.

[d] The leachate analyses and the volume of water applied during the last four months of the monitoring program were not included in the calculations because only the drain leachates were sampled and analyzed.

[e] The values include only the constituents leached from the residue. The quantities of metals and ions resulting from the applied water were not included in the calculations.

TABLE 61. COMPARISON OF SANITARY LANDFILL COLUMN LEACHATE CONSTITUENTS WITH SURFACE WATER CRITERIA FOR MUNICIPAL WATER SUPPLIES[d]

Residue Type and Sample Point	Total Water (liters)	Percent Constituent Exceeded Water Quality Criteria[e]				
		Cl (250 mg/l)[a,b]	SO_4 (250 mg/l)[b]	Fe (0.3 mg/l)[b]	Pb (0.05 mg/l)[c]	Zn (5.0 mg/l)[b]
NJFA						
Top Lysimeter	447	0	52	--	95	0
Middle Lysimeter	355	0	56	--	72	0
Bottom Lysimeter	262	0	69	--	59	0
Drain	169	0	33	--	47	0
Average		0	53		68	0
NJSBM						
Top Lysimeter	577	0	34	--	75	0
Middle Lysimeter	537	0	30	--	68	0
Bottom Lysimeter	496	0	22	--	63	0
Drain	447	0	27	--	50	0
Average		0	28		64	0
VFA						
Top Lysimeter	461	0	9	--	55	0
Middle Lysimeter	424	0	10	--	54	0
Bottom Lysimeter	387	0	9	--	59	0
Drain	353	0	6	--	58	0
Average			9		57	0
VSBM						
Top Lysimeter	595	0	44	--	74	0
Middle Lysimeter	517	0	44	--	85	0
Bottom Lysimeter	443	0	53	--	70	0
Drain	368	0	47	--	64	0
Average		0	47		74	0
EFA						
Top Lysimeter	666	3	90	--	84	0
Middle Lysimeter	554	7	94	--	65	0
Bottom Lysimeter	443	21	95	--	59	0
Drain	330	9	98	--	47	0
Average		10	94		64	0
ESBM						
Top Lysimeter	564	8	13	--	68	0
Middle Lysimeter	466	4	38	--	66	0
Bottom Lysimeter	373	17	35	--	64	0
Drain	285	16	15	--	67	0
Average		11	26		66	0

[a] Permissible criteria for each constituent is given in parenthesis.

[b] Water quality criteria for municipal water supply.

[c] Maximum contaminant level for the EPA interim primary drinking water regulation, 1977.

[d] The leachate analyses and the volume of water applied during the last four months of the monitoring program were not included in the calculations because only the drain leachate were sampled and analyzed.

[e] The values include only the constituents leached from the residue. The quantities of metals and ions resulting from the applied water were not included in the calculations.

TABLE 62. COMPARISON OF COAL COLUMN LEACHATE CONSTITUENTS WITH WATER QUALITY CRITERIA FOR MUNICIPAL WATER SUPPLIES[d]

Residue Type and Sample Point	Total Water (liters)	Percent Constituent Exceeded Water Quality Criteria[e]				
		Cl (250 mg/l)[a,b]	SO_4 (250 mg/l)[b]	Fe (0.3 mg/l)[b]	Pb (0.05 mg/l)[c]	Zn (5.0 mg/l)[b]
NJFA						
Top lysimeter	561	0	89	7	76	0
Middle lysimeter	508	0	90	8	72	0
Bottom lysimeter	454	0	89	4	53	0
Drain	401	0	92	5	53	0
Average		0	90	6	63	0
NJSBM						
Top lysimeter	826	0	87	7	73	0
Middle lysimeter	722	0	90	6	53	0
Bottom lysimeter	620	0	86	5	35	0
Drain	517	0	79	4	65	0
Average		0	86	6	56	0
VFA						
Top lysimeter	844	0	27	4	51	0
Middle lysimeter	781	0	66	4	75	0
Bottom lysimeter	719	0	29	0	47	0
Drain	657	0	30	4	58	0
Average		0	38	3	58	0
VSBM						
Top lysimeter	422	0	68	6	58	0
Middle lysimeter	367	0	59	8	59	0
Bottom lysimeter	297	0	58	9	59	0
Drain	231	0	60	0	37	0
Average		0	61	6	53	0
EFA						
Top lysimeter	590	10	87	0	74	0
Middle lysimeter	468	10	84	2	91	0
Bottom lysimeter	346	10	81	3	66	0
Drain	224	0	70	0	89	0
Average		8	81	1	80	0
ESBM						
Top lysimeter	602	15	33	6	96	0
Middle lysimeter	487	11	45	10	93	0
Bottom lysimeter	371	4	46	7	86	0
Drain	256	13	34	9	74	0
Average		11	39	8	87	0

[a] Permissible criteria for each constituent is given in parenthesis.

[b] Water quality criterial for municipal water supply.

[c] Maximum contaminant level for the EPA interim primary drinking water regulation, 1977.

[d] The leachate analyses and the volume of water applied during the last four months of the monitoring program were not included in the calculations because only the drain leachates were sampled and analyzed.

[e] The values include only the constituents leached from the residue. The quantities of metals and ions resulting from the applied water were not included in the calculations.

TABLE 63 . COMPARISON OF SANDY, CLAYEY, AND SILTY SOILS COLUMN LEACHATE CONSTITUENTS WITH WATER QUALITY CRITERIA FOR MUNICIPAL WATER SUPPLIES[d]

Residue Type and Sample Point	Total Water (liters)	Percent Constituent Exceeded Water Quality Criteria[e]				
		Cl (250 mg/l)[a,b]	SO_4 (250 mg/l)[b]	Fe (0.3 mg/l)[b]	Pb (0.05 mg/l)[c]	Zn (5.0 mg/l)[b]
Sandy Loam						
EFA						
Top Lysimeter	224	3	71	80	53	0
Middle Lysimeter	202	3	45	86	49	0
Bottom Lysimeter	177	11	25	66	31	0
Drain	156	11	34	80	43	0
Average		7	44	78	44	0
ESBM						
Top Lysimeter	394	13	58	12	56	0
Middle Lysimeter	291	18	41	14	57	0
Bottom Lysimeter	201	27	22	63	66	0
Drain	112	18	5	57	24	0
Average		19	31	36	50	0
Clay Loam						
EFA						
Top Lysimeter	171	0	95	60	60	0
Middle Lysimeter	123	19	93	59	59	0
Bottom Lysimeter	89	11	66	40	42	0
Drain	61	4	64	51	76	0
Average		9	80	53	59	0
VSBM						
Top Lysimeter	254	37	46	43	70	0
Middle Lysimeter	202	44	46	37	72	0
Bottom Lysimeter	141	13	71	56	90	0
Drain	79	30	57	54	78	0
Average		31	55	47	77	0
Silty Loam						
EFA						
Top Lysimeter	575	0	53	4	68	0
Middle Lysimeter	430	0	63	3	76	0
Bottom Lysimeter	294	13	51	8	80	0
Drain	163	1	41	2	94	0
Average		3	52	4	80	0
ESBM						
Top Lysimeter	585	18	3	4	78	0
Middle Lysimeter	479	20	19	0	78	0
Bottom Lysimeter	366	20	0	0	68	0
Drain	265	20	19	0	98	0
Average		19	10	1	80	0

[a] Permissible criteria for each constituent is given in parenthesis.

[b] Water quality criteria for municipal water supply.

[c] Maximum contaminant level for the EPA interim primary drinking water regulation, 1977.

[d] The leachate analyses and the volume of water applied during the last four months of the monitoring program were not included in the calculations because only the drain leachates were sampled and analyzed.

[e] The values include only the constituents leached from the residue. The quantities of metals and ions resulting from the applied water were not included in the calculations.

were the NJSBM and VFA leachates from the sanitary landfill test columns. Only 9 and 28 percent of the leachate, respectively, exceeded the water quality criteria. Likewise, the ESBM added to the dolomite, sanitary landfill, and the sandy and silty soil simulated environments resulted in relatively low sulfate concentrations. For nearly all the test columns more than 90 percent of the leachate exceeded the Environmental Protection Agency maximum contaminant level for lead; whereas, only 7 percent of the leachate volume exceeded the recommended iron concentration. Some 35 to 80 percent of the EFA and ESBM leachates from the sandy and clayey soil test columns exceeded the recommended surface water limits for iron; however, as mentioned earlier in this chapter, the excessively high iron concentrations were probably due to iron leached from the soils. The recommended water quality criteria for zinc was not exceeded.

In general, the VFA showed the lowest percentage of leached contaminants which exceed the water quality criteria and, hence, appeared to contribute the shortest pollution creation period. Similarly, the sanitary landfill and the coal column test environments showed the lowest percentages of leachate volume for which the constituents appear to present the best environments for disposing fluidized-bed residues, particularly for the VFA type. The ocean simulated environment was not evaluated for constituent contamination because of the high concentrations of some constituents attributed to the sea water.

Summary of Addition Analytical Results

After the 40th week of the test columns operation, the leachates were analyzed for additional constituents. These constituents included aluminum, calcium, cadmium, copper, mercury, boron, chemical oxygen demand (COD), nitrate-nitrogen, and total organic carbon. Since these tests were not started until after the 40th week of the test columns operation, and a maximum of five analyses were determined for each constituent, only preliminary evaluation of the results could be done. The minimum, maximum, and average values for these constituents are tabulated in Tables 64 to 70 . Included in these tables are the continued test results for pH, specific conductance, and total dissolved solids.

The recommended irrigation water contaminant level for aluminum was not exceeded in the leachate samples from any of the test columns. The highest levels of aluminum (above 1.0 m/l) were found in the ESBM leachate from the limestone, dolomite, sanitary landfill, coal mine and clayey soil test columns, while most of the other test columns leached less than 0.5 mg/l of aluminum. The cadmium concentration in the drain leachates generally did not exceed the municopal water quality criteria of 0.01 mg/l. The only exceptions were the NJFA and NJSBM leachates from the dolomite simulated environments and the NJSBM leachate from the coal mine test column; the concentrations averaged only 0.02 mg/l.

In general, the leachates from sanitary landfill test columns were higher than from the other simulated environments, and the VFA leached less calcium than the other fluidized-bed materials. The ocean simulated disposal sites showed high concentrations of calcium, but much of this was due to the calcium content in the applied sea water.

TABLE 64. LEACHATE ANALYSES OF THE TEST COLUMNS FROM THE NJFA[a]

Environment Test Column	Aluminum (5.0 mg/l)[a,b,c]			Cadmium (0.01 mg/l)[d]			Calcium (no criteria)			Copper (1.0 mg/l)[d]			Mercury (0.005 mg/l)[e]		
	Avg.[f]	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Limestone															
Top lysimeter	0.33	0.30	0.40	<0.01	<0.01	0.02	272	171	425	0.01	<0.01	0.02	0.0004	0.0003	0.0006
Bottom lysimeter	0.55	0.50	0.6	0.01	<0.01	0.04	237	160	275	0.01	<0.01	0.04	0.0011	0.0011	0.0011
Drain	0.43	0.29	0.80	<0.01	<0.01	0.06	228	109	500	<0.01	<0.01	0.06	0.0006	0.0005	0.0012
Dolomite															
Top lysimeter	0.17	0.1	0.2	0.01	<0.01	0.02	386	282	450	0.01	0.01	0.02	0.0003	<0.0002	0.0006
Bottom lysimeter	0.27	0.1	0.5	0.02	0.01	0.04	408	264	460	0.02	0.01	0.04	0.0002	<0.0002	0.0003
Drain	0.38	0.20	0.70	0.02	<0.01	0.03	260	202	480	0.02	0.01	0.03	0.0004	<0.0002	0.0005
Sanitary landfill															
Top lysimeter	0.05	<0.02	0.10	<0.01	<0.01	0.02	401	160	675	<0.01	<0.01	0.01	<0.0002	<0.0002	<0.0002
Middle lysimeter	0.23	<0.02	0.50	<0.01	<0.01	0.01	362	262	515	<0.01	<0.01	0.02	0.0004	0.0003	0.0006
Bottom lysimeter	0.13	0.10	0.20	0.01	<0.01	0.03	306	127	515	0.01	<0.01	0.03	0.0007	0.0003	0.0010
Drain	0.14	0.11	0.20	0.01	<0.01	0.06	333	107	480	0.01	<0.01	0.06	0.0006	0.0003	0.0010
Coal mine															
Top lysimeter	0.1	<0.02	0.20	<0.01	<0.01	0.01	232	164	270	<0.01	<0.01	0.01	--	--	--
Middle lysimeter	0.37	0.10	0.30	<0.01	<0.01	0.01	261	144	370	<0.01	<0.01	0.01	0.0006	0.0006	0.0006
Bottom lysimeter	0.27	0.20	0.30	<0.01	<0.01	0.01	248	138	365	<0.01	<0.01	0.01	0.0004	0.0004	0.0004
Drain	0.17	0.13	0.30	<0.01	<0.01	0.01	161	101	325	<0.01	<0.01	0.01	0.0006	0.0005	0.0012
Ocean															
Top lysimeter	0.07	<0.02	0.10	0.08	0.06	0.09	955	420	2,400	0.08	0.06	0.09	0.0003	0.0003	0.0003
Drain	0.22	0.20	0.30	0.09	0.05	0.11	540	202	2,400	0.09	0.05	0.11	0.0005	0.0003	0.0006

Continued

TABLE 64 (Continued)

Environment Test Column	Boron (1.0 mg/l)[d] Avg.[f]	Min.	Max.	Nitrate as Nitrogen (10 mg/l as N)[e] Avg.	Min.	Max.	pH (6.0 to 8.5)[d] Avg.	Min.	Max.	Specific Conductance (μmhos) Avg.	Min.	Max.
Limestone												
Top lysimeter	1.00	0.55	1.30	0.43	0.16	0.70	8.8	8.15	9.5	1,540	1,490	1,570
Bottom lysimeter	0.03	0.10	0.45	0.31	0.09	0.53	9.0	7.55	11.5	2,090	1,460	3,250
Drain	1.20	0.60	1.55	1.53	0.23	2.10	8.1	7.8	8.55	1,570	1,320	1,970
Dolomite												
Top lysimeter	0.50	0.15	0.65	0.25	0.14	0.35	8.8	8.05	9.55	2,360	1,590	2,960
Bottom lysimeter	0.50	0.15	0.80	0.27	0.19	0.35	8.9	8.5	9.3	2,240	1,850	2,510
Drain	0.80	0.30	1.00	0.71	0.14	3.50	9.2	8.75	9.5	2,200	1,450	2,650
Sanitary landfill												
Top lysimeter	0.40	0.40	0.40	0.49	0.07	0.90	6.9	6.75	7.2	2,315	2,160	2,470
Middle lysimeter	0.45	0.45	0.50	1.28	<0.01	2.56	7.4	7.0	7.8	1,680	1,350	2,010
Bottom lysimeter	0.50	0.40	0.60	0.45	0.19	0.70	7.6	7.25	8.05	1,545	1,440	1,650
Drain	2.60	0.40	4.20	1.09	0.92	1.61	7.25	7.1	7.5	1,460	1,370	1,670
Coal Mine												
Top lysimeter	0.70	0.50	0.80	0.92	0.43	1.40	7.8	7.6	8.2	1,460	1,340	1,580
Middle lysimeter	0.60	0.50	0.70	0.88	0.34	1.41	8.5	7.5	9.7	1,620	1,530	1,700
Bottom lysimeter	0.70	0.70	0.70	0.83	0.25	1.41	9.3	8.8	10.1	1,560	1,430	1,690
Drain	1.00	0.50	1.30	0.70	0.23	2.92	8.45	7.5	11.1	1,350	1,250	1,570
Ocean												
Top lysimeter	1.55	0.10	2.95	0.99	0.99	0.99	7.3	7.1	7.7	48,800	45,000	52,600
Drain	3.60	1.70	4.10	0.26	0.18	0.6	7.05	6.8	7.35	38,900	36,000	45,400

[a] All constituents are reported in mg/l unless otherwise noted.

[b] The value in parentheses is the permissible contamination level as presented in Tables 56 and 57.

[c] Recommended maximum concentration in irrigation waters (see Table 57).

[d] Municipal water quality criteria (see Table 56).

[e] EPA interim primary drinking water regulation (see Table 56).

[f] Avg = Includes the average of 2 to 4 analyses of monthly composites and one analysis of a four-month composite.

TABLE 65. LEACHATE ANALYSES OF THE TEST COLUMNS FROM THE NJSBM

Environment Test Column	Aluminum (5.0 mg/l)[a,b,c]			Cadmium (0.01 mg/l)[d]			Calcium (no criteria)			Copper (1.0 mg/l)[d]			Mercury (0.005 mg/l)[e]		
	Avg.[f]	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Limestone															
Top lysimeter	0.20	0.10	0.30	<0.01	<0.01	0.02	552	128	900	<0.01	<0.01	0.02	--	--	--
Bottom lysimeter	0.33	0.20	0.50	0.02	<0.01	0.05	245	315	106	<0.01	0.02	0.05	--	--	--
Drain	0.11	0.09	0.20	<0.01	<0.01	0.02	290	115	900	<0.01	<0.01	0.03	0.0018	<0.0002	0.0021
Dolomite															
Top lysimeter	0.20	0.10	0.30	0.01	<0.01	0.03	712	375	1,180	0.04	<0.01	0.10	0.0006	0.0005	0.0007
Bottom lysimeter	0.33	0.20	0.50	0.02	<0.01	0.06	547	370	900	0.02	<0.01	0.06	--	--	--
Drain	0.16	0.14	0.20	0.02	<0.01	0.02	380	205	652	0.03	<0.01	0.10	0.0027	<0.0002	0.0042
Sanitary landfill															
Top lysimeter	0.33	0.20	0.50	<0.01	<0.01	0.01	800	500	1,100	<0.01	<0.01	0.01	0.0020	<0.0002	0.0050
Middle lysimeter	0.17	0.10	0.20	<0.01	<0.01	0.01	334	125	670	<0.01	<0.01	0.01	0.0003	0.0003	0.0003
Bottom lysimeter	0.20	0.10	0.30	<0.01	<0.01	0.01	227	68	280	<0.01	<0.01	0.01	0.0040	0.0040	0.0040
Drain	0.41	0.10	0.60	<0.01	<0.01	0.01	236	156	480	<0.01	<0.01	0.02	0.0004	0.0002	0.0005
Coal mine															
Top lysimeter	--	--	--	0.02	0.02	0.03	--	--	--	0.02	0.02	0.03	--	--	--
Middle lysimeter	0.15	0.10	0.20	0.02	<0.01	0.03	232	126	300	0.02	0.01	0.03	--	--	--
Bottom lysimeter	0.23	0.10	0.50	0.01	<0.01	0.05	237	136	350	0.02	<0.01	0.05	0.0009	0.0009	0.0009
Drain	0.13	0.10	0.30	0.02	<0.01	0.10	295	202	615	0.03	<0.01	0.10	0.0007	0.0003	0.0019
Ocean															
Top lysimeter	0.07	<0.02	0.10	0.06	0.06	0.06	1,027	255	3,400	0.06	0.06	0.06	0.0005	0.0005	0.0005
Drain	0.42	0.20	0.51	0.09	0.06	0.11	950	255	3,500	0.09	0.06	0.11	0.0026	0.0002	0.0038

Continued

TABLE 65 (Continued)

Environment Test Column	Boron (1.0 mg/l)[d]			Nitrate as Nitrogen[e] (10 mg/l as N)			pH[d] (6.0 to 8.5)			Specific Conductance (μ mhos)		
	Avg.[f]	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Limestone												
Top lysimeter	0.20	<0.10	0.25	0.34	0.34	0.34	10.8	8.1	12.2	4,870	3,990	5,750
Bottom lysimeter	0.15	<0.01	0.25	0.35	0.35	0.35	10.2	8.3	12.2	2,220	1,450	2,990
Drain	0.45	<0.10	0.60	0.36	0.20	0.44	12.0	11.8	12.4	3,080	1,860	5,440
Dolomite												
Top lysimeter	0.25	<0.10	0.45	0.34	0.34	0.34	12.5	12.4	12.6	8,770	8,500	8,970
Bottom lysimeter	0.10	<0.10	0.20	1.32	1.32	1.32	10.2	8.6	11.9	2,660	1,150	4,180
Drain	0.40	<0.10	0.50	0.26	0.13	0.70	12.1	11.9	12.4	4,490	3,615	4,770
Sanitary landfill												
Top lysimeter	0.30	0.20	0.35	--	--	--	12.2	12.0	12.4	7,720	7,420	8,110
Middle lysimeter	0.15	0.10	0.20	0.30	<0.01	0.60	9.2	7.55	11.9	2,660	1,660	3,660
Bottom lysimeter	0.20	0.10	0.35	2.17	0.53	3.80	9.0	7.45	11.9	2,380	1,600	3,770
Drain	0.30	0.10	0.45	0.35	0.10	1.32	9.7	6.8	11.7	2,375	1,780	2,760
Coal mine												
Top lysimeter	0.30	0.30	0.30	--	--	--	--	--	--	1,380	1,380	1,380
Middle lysimeter	0.75	0.70	0.80	1.86	1.86	1.86	8.2	7.8	8.55	1,450	1,320	1,550
Bottom lysimeter	0.60	0.40	0.75	0.80	0.25	1.34	8.0	7.6	8.8	1,560	1,460	1,610
Drain	2.50	0.10	4.20	0.55	0.36	1.32	12.0	11.9	12.2	3,620	3,120	4,800
Ocean												
Top lysimeter	2.60	2.60	2.65	0.32	0.32	0.32	7.45	7.2	7.75	35,100	33,200	38,400
Drain	4.20	4.00	4.30	0.22	0.16	0.46	7.9	7.75	8.3	39,300	36,000	48,400

[a] All constituents are reported in mg/l unless otherwise noted.

[b] The value in parentheses is the permissible contamination level as presented in Tables 56 and 57.

[c] Recommended maximum concentration in irrigation waters (see Table 57).

[d] Municipal water quality criteria (see Table 56 .).

[e] EPA interim primary drinking water regulation (see Table 56).

[f] Avg = Includes the average of 2 to 4 analyses of monthly composites and one analysis of a four-month composite.

TABLE 66. LEACHATE ANALYSES OF THE TEST COLUMNS FROM THE VFA

Environment Test Column	Aluminum (5.0 mg/l)^{a,b,c}			Cadmium (0.01 mg/l)^{d}			Calcium (no criteria)			Copper (1.0 mg/l)^{d}			Mercury (0.005 mg/l)^{e}		
	Avg.^{f}	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Limestone															
Top lysimeter	0.23	0.10	0.40	<0.01	<0.01	0.01	84	57	120	<0.01	<0.01	0.01	0.0006	0.0006	0.0006
Bottom lysimeter	0.20	0.20	0.20	<0.01	<0.01	0.01	126	70	215	<0.01	<0.01	0.01	0.0005	0.0004	0.0005
Drain	0.39	0.34	0.60	<0.01	<0.01	0.02	84	58	170	<0.01	<0.01	0.02	0.0006	0.0005	0.0012
Dolomite															
Top lysimeter	0.40	0.20	0.70	<0.01	<0.01	0.01	111	93	140	<0.01	<0.01	0.01	0.0003	0.0002	0.0004
Bottom lysimeter	0.43	0.30	0.70	0.03	<0.01	0.07	116	106	135	0.02	0.01	0.02	--	--	--
Drain	0.42	0.30	0.70	<0.01	<0.01	0.04	62	51	105	<0.01	<0.01	0.04	0.0004	<0.0002	0.0005
Sanitary landfill															
Top lysimeter	0.13	<0.02	0.20	<0.01	<0.01	0.01	195	88	230	<0.01	<0.01	0.01	0.0004	0.0003	0.0004
Middle lysimeter	0.20	0.10	0.30	<0.01	<0.01	0.01	195	91	290	<0.01	<0.01	0.01	0.0003	0.0002	0.0004
Bottom lysimeter	0.10	0.10	0.10	0.01	<0.01	0.03	188	102	250	0.01	<0.01	0.03	-	--	--
Drain	1.32	0.20	1.90	<0.01	<0.01	0.03	159	60	260	<0.01	<0.01	0.03	0.0005	0.0005	0.0006
Coal mine															
Top lysimeter	0.03	<0.02	0.10	<0.01	<0.01	0.01	185	110	245	<0.01	<0.01	0.01	0.0006	0.0006	0.0006
Middle lysimeter	0.25	0.20	0.30	<0.01	<0.01	0.01	188	122	230	<0.01	<0.01	0.01	--	--	--
Bottom lysimeter	0.23	0.10	0.40	<0.01	<0.01	0.01	184	125	240	<0.01	<0.01	0.01	0.0003	0.0003	0.0003
Drain	0.36	0.09	1.10	<0.01	<0.01	0.01	143	108	220	<0.01	<0.01	0.01	0.0005	0.0003	0.0007
Ocean															
Top lysimeter	0.13	0.10	0.20	0.06	0.05	0.09	795	106	2,025	0.07	0.05	0.09	0.0009	0.0009	0.0009
Drain	0.29	0.20	0.6	0.09	0.05	0.11	403	173	2,050	0.09	0.05	0.11	0.0006	0.0006	0.0037

Continued

TABLE 66 (Continued)

Environment Test Column	Boron (1.0 mg/l)[d]			Nitrate as Nitrogen[e] (10 mg/l as N)			pH[d] (6.0 to 8.5)			Specific Conductance (μ mhos)		
	Avg.[f]	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Limestone												
Top lysimeter	0.40	0.15	0.55	0.30	0.26	0.35	8.7	8.2	9.5	620	609	630
Bottom lysimeter	0.25	<0.10	0.60	0.24	0.04	0.44	9.0	8.5	9.7	850	800	900
Drain	0.85	<0.10	1.32	0.45	0.05	0.58	11.3	10.5	11.8	1,470	775	1,800
Dolomite												
Top lysimeter	1.10	0.85	1.20	0.70	<0.01	1.40	8.45	7.85	9.2	735	680	790
Bottom lysimeter	0.75	0.50	1.00	0.26	0.26	0.26	8.0	7.75	8.3	1,470	1,470	1,470
Drain	1.80	1.20	2.05	0.01	<0.01	0.02	8.0	7.5	9.3	715	635	820
Sanitary landfill												
Top lysimeter	0.95	0.75	1.00	0.97	0.97	0.97	7.3	7.05	7.5	1,320	660	1,810
Middle lysimeter	0.95	0.90	1.00	0.13	<0.01	0.26	7.25	6.6	7.75	1,350	500	2,060
Bottom lysimeter	0.95	0.75	1.15	3.10	3.10	3.10	7.1	7.0	7.2	1,410	520	2,020
Drain	1.30	0.85	1.50	0.13	<0.01	0.26	7.3	7.0	7.35	1,185	960	1,780
Coal mine												
Top lysimeter	1.00	0.85	1.10	2.38	1.10	3.66	8.8	8.7	8.9	1,240	700	1,670
Middle lysimeter	0.90	0.80	1.10	1.94	0.34	3.54	8.6	8.0	9.1	1,190	740	1,570
Bottom lysimeter	0.95	0.75	1.10	1.75	0.39	3.10	8.9	8.5	9.4	1,300	700	1,690
Drain	0.40	<0.10	0.95	1.06	0.26	4.43	7.7	7.5	8.5	1,710	615	2,890
Ocean												
Top lysimeter	3.50	1.70	5.30	--	--	--	7.8	7.7	7.9	39,500	38,600	40,500
Drain	5.10	1.70	5.85	3.60	3.60	3.60	7.8	7.55	8.1	38,800	36,000	44,800

[a] All constituents are reported in mg/l unless otherwise noted.

[b] The value in parentheses is the permissible contamination level as presented in Tables 56 and 57 .

[c] Recommended maximum concentration in irrigation waters (see Table 57).

[d] Municipal water quality criteria (see Table 56).

[e] EPA interim primary drinking water regulation (see Table 56).

[f] Avg = Includes the average of 2 to 4 analyses of monthly composites and one analysis of a four-month composite.

TABLE 67 . LEACHATE ANALYSES OF THE TEST COLUMNS FROM THE VSBM

Environment Test Column	Aluminum (5.0 mg/l)[a,b,c]			Cadmium (0.01 mg/l)[d]			Calcium (no criteria)			Copper (1.0 mg/l)[d]			Mercury (0.005 mg/l)[e]		
	Avg.[f]	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Limestone															
Top lysimeter	0.23	0.20	0.30	0.01	<0.01	0.04	309	184	450	0.02	<0.01	0.04	0.0006	0.0006	0.0006
Bottom lysimeter	0.30	0.30	0.30	<0.01	<0.01	0.01	153	80	190	<0.01	<0.01	0.01	0.0008	0.0007	0.0008
Drain	0.50	0.33	1.20	<0.01	<0.01	0.01	86	80	110	<0.01	<0.01	0.01	0.0009	<0.0002	0.0012
Dolomite															
Top lysimeter	0.25	0.20	0.30	0.02	<0.01	0.05	235	160	390	0.02	<0.01	0.05	--	--	--
Bottom lysimeter	0.24	<0.02	0.50	0.01	<0.01	0.03	246	20	415	0.01	<0.01	0.03	--	--	--
Drain	0.21	0.19	0.30	<0.01	<0.01	0.01	234	26	900	<0.01	<0.01	0.01	0.0005	0.0002	0.0006
Sanitary landfill															
Top lysimeter	0.05	<0.02	0.01	<0.01	<0.01	<0.01	58	34	70	<0.01	<0.01	<0.01	0.0004	0.0004	0.0004
Middle lysimeter	0.33	0.20	0.50	<0.01	<0.01	<0.01	147	38	250	<0.01	<0.01	<0.01	0.0002	0.0002	0.0003
Bottom lysimeter	0.30	0.20	0.40	<0.01	<0.01	0.01	165	14	225	<0.01	<0.01	0.01	--	--	--
Drain	0.14	0.09	0.20	<0.01	<0.01	0.02	318	168	480	<0.01	<0.01	0.02	0.0004	0.0002	0.0005
Coal mine															
Top lysimeter	0.33	<0.02	0.60	<0.01	<0.01	0.01	424	202	675	<0.01	<0.01	0.01	--	--	--
Middle lysimeter	0.13	<0.02	0.20	<0.01	<0.01	0.01	327	181	525	<0.01	<0.01	0.01	0.0009	0.0009	0.0009
Bottom lysimeter	0.30	0.10	0.90	<0.01	<0.01	0.01	296	170	482	<0.01	<0.01	0.01	--	--	--
Drain	0.24	0.12	0.70	<0.01	<0.01	0.01	334	127	515	<0.01	<0.01	0.01	0.0006	0.0005	0.0005
Ocean															
Top lysimeter	0.30	0.10	0.50	0.04	0.03	0.07	1,403	522	3,400	-	--	--	--	--	--
Bottom lysimeter	0.35	0.20	0.64	0.04	0.03	0.05	1,552	782	2,300	0.05	0.03	0.06	0.0010	0.0010	0.0010
Drain	0.23	0.30	0.54	0.10	0.07	0.20	2,370	1,100	5,020	0.10	0.06	0.20	0.0032	0.0006	0.0040

Continued

TABLE 67 (Continued)

Environment Test Column	Boron (1.0 mg/l)[d] Avg.[f]	Min.	Max.	Nitrate as Nitrogen[e] (10 mg/l as N) Avg.	Min.	Max.	pH[d] (6.0 to 8.5) Avg.	Min.	Max.	Specific Conductance (μ mhos) Avg.	Min.	Max.
Limestone												
Top lysimeter	0.10	<0.10	0.15	0.33	0.21	0.44	10.3	9.0	11.8	2,060	1,815	2,530
Bottom lysimeter	0.10	<0.10	0.10	0.30	0.15	0.44	10.7	10.4	11.2	1,310	1,190	1,430
Drain	0.60	<0.10	0.90	0.14	0.08	0.35	9.5	11.7	8.2	1,130	1,080	1,240
Dolomite												
Top lysimeter	0.10	<0.10	0.20	0.35	0.35	0.35	9.8	7.9	11.8	2,560	1,645	3,470
Bottom lysimeter	<0.10	<0.10	<0.10	0.26	0.26	0.26	10.2	8.3	12.0	2,500	1,260	3,120
Drain	0.40	<0.10	0.55	0.23	0.16	0.40	11.9	11.8	12.4	2,970	1,680	5,750
Sanitary landfill												
Top lysimeter	0.15	0.10	0.15	0.13	0.07	0.19	7.8	7.3	8.3	895	790	1,000
Middle lysimeter	0.15	<0.10	0.25	<0.01	<0.01	<0.01	7.6	7.3	8.3	1,180	1,140	1,220
Bottom lysimeter	0.55	0.10	0.90	1.17	0.84	1.50	9.0	7.45	11.65	1,480	1,440	1,530
Drain	1.05	0.15	1.75	0.48	0.16	1.50	7.3	7.2	7.6	1,700	1,440	2,080
Coal mine												
Top lysimeter	0.25	0.15	0.45	0.97	0.97	0.97	11.4	11.2	11.5	2,330	1,750	2,990
Middle lysimeter	0.10	0.10	0.15	2.04	0.53	3.54	10.6	8.4	11.8	1,890	1,540	2,310
Bottom lysimeter	0.15	0.10	0.20	0.88	0.88	0.88	11.2	10.8	11.6	1,970	1,670	2,270
Drain	0.50	0.10	0.75	0.85	0.22	3.54	11.0	8.2	12.0	2,740	1,390	3,480
Ocean												
Top lysimeter	0.25	<0.01	0.45	0.34	0.34	0.34	10.8	9.1	11.8	27,600	15,600	40,600
Drain	0.20	0.10	0.50	0.50	0.26	0.56	11.8	11.5	12.2	44,400	37,100	47,100

[a] All constituents are reported in mg/l unless otherwise noted.

[b] The value in parentheses is the permissible contamination level as presented in Tables 56 and 57.

[c] Recommended maximum concentration in irrigation waters (see Table 57).

[d] Municipal water quality critieria (see Table 56).

[e] EPA interim primary drinking water regulation (see Table 56).

[f] Avg = Includes the average of 2 to 4 analyses of monthly composites and one analysis of a four-month composite.

TABLE 68. LEACHATE ANALYSES OF THE TEST COLUMNS FROM THE EFA

Environment Test Column	Aluminum (5.0 mg/l)[a,b,c]			Cadmium (0.01 mg/l)[d]			Calcium (no criteria)			Copper (1.0 mg/l)[d]			Mercury (0.005 mg/l)[e]		
	Avg.[f]	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Limestone															
Top lysimeter	0.10	0.10	0.10	0.03	0.01	0.05	386	290	560	0.02	0.01	0.05	0.0009	0.0009	0.0009
Bottom lysimeter	0.25	0.10	0.40	0.01	0.01	0.01	468	252	740	0.01	0.01	0.01	0.0004	0.0002	0.0009
Drain	0.21	0.02	0.30	0.02	<0.01	0.04	229	80	520	<0.01	<0.01	0.04	0.0005	0.0002	0.0012
Dolomite															
Top lysimeter	0.13	0.10	0.20	0.02	<0.01	0.03	1,160	705	1,800	0.02	<0.01	0.03	0.0009	0.0009	0.0009
Bottom lysimeter	0.65	0.10	1.40	0.02	<0.01	0.05	415	297	550	0.02	<0.01	0.05	0.0010	<0.0002	0.0015
Drain	1.56	0.10	2.19	<0.01	<0.01	<0.01	200	74	550	<0.01	<0.01	<0.01	0.0007	0.0003	0.0015
Sanitary landfill															
Top lysimeter	0.25	0.10	0.40	0.02	0.01	0.02	665	600	760	0.02	0.01	0.02	0.0015	0.0008	0.0024
Middle lysimeter	0.03	<0.02	0.10	<0.01	<0.01	0.01	602	325	1,050	<0.01	<0.01	0.01	0.0010	0.0008	0.0012
Bottom lysimeter	0.23	0.10	0.50	<0.01	<0.01	0.01	586	508	625	<0.01	<0.01	0.01	0.0022	0.0005	0.0037
Drain	0.17	0.05	0.20	<0.01	<0.01	0.01	451	230	585	<0.01	<0.01	0.01	0.0010	0.0005	0.0030
Coal mine															
Top lysimeter	0.37	0.10	0.70	0.02	<0.01	0.07	402	275	550	0.02	<0.01	0.07	--	--	--
Middle lysimeter	0.20	<0.02	0.30	<0.01	<0.01	0.01	498	430	575	<0.01	<0.01	0.01	0.0002	<0.0001	0.0004
Bottom lysimeter	0.27	0.10	0.60	<0.01	<0.01	0.01	606	353	1,150	<0.01	<0.01	0.01	0.0022	0.0002	0.0060
Drain	0.46	0.30	0.80	<0.01	<0.01	<0.01	298	111	750	<0.01	<0.01	<0.01	0.0010	0.0006	0.0018
Ocean															
Top lysimeter	0.20	0.10	0.40	0.06	0.01	0.08	835	380	1,290	0.04	0.01	0.08	--	--	--
Drain	0.28	0.10	0.34	0.07	0.06	0.14	1,930	1,200	3,500	0.07	0.06	0.14	0.0023	<0.0002	0.0036

Continued

TABLE 68' (Continued)

Environment Test Column	Aluminum			Cadmium			Calcium			Copper			Mercury		
	Avg.[f]	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max
Sandy soil															
Top lysimeter	0.23	<0.02	0.70	0.02	<0.01	0.05	277	210	360	0.03	<0.01	0.05	0.0018	0.0014	0.0024
Middle lysimeter	0.40	<0.02	0.70	0.02	0.01	0.03	291	237	365	0.02	0.01	0.03	0.0012	0.0008	0.0018
Bottom lysimeter	0.07	<0.02	0.10	0.02	0.01	0.03	130	75	178	0.02	0.01	0.03	0.0004	0.0002	0.0006
Drain	0.23	0.08	0.70	0.01	<0.01	0.03	144	110	255	0.01	<0.01	0.03	0.0009	0.0004	0.0034
Clayey soil															
Top lysimeter	0.27	0.20	0.40	<0.01	<0.01	0.01	554	193	915	<0.01	<0.01	0.01	0.0009	0.0001	0.0017
Middle lysimeter	0.08	<0.02	0.10	<0.01	0.01	0.01	370	200	540	0.01	0.01	0.01	0.0007	0.0004	0.0009
Bottom lysimeter	0.23	<0.02	0.30	<0.01	<0.01	0.01	423	230	615	<0.01	<0.01	0.01	0.0004	0.0003	0.0005
Drain	5.78	0.20	9.86	0.01	<0.01	0.03	103	40	353	0.01	<0.01	0.03	0.0005	0.0003	0.0009
Silty soil															
Top lysimeter	0.28	<0.02	0.70	<0.01	<0.01	0.01	322	65	730	<0.01	<0.01	0.01	0.0007	0.0001	0.0013
Middle lysimeter	0.38	<0.02	1.00	<0.01	<0.01	0.01	257	46	660	<0.01	<0.01	0.01	0.0010	0.0007	0.0012
Bottom lysimeter	0.55	0.20	0.90	<0.01	<0.01	0.01	174	50	270	<0.01	<0.01	0.01	0.0004	0.0001	0.0007
Drain	0.98	0.10	1.55	<0.01	<0.01	<0.01	426	287	480	<0.01	<0.01	<0.01	0.0013	0.0003	0.0057

Continued

TABLE 68 (Continued)

Environment Test Column	Boron (1.0 mg/l)^d Avg.	Min.	Max.	Nitrate as Nitrogen^e (10 mg/l as N) Avg.	Min.	Max.	pH^d (6.0 to 8.5) Avg.	Min.	Max.	Specific Conductance (μ mhos) Avg.	Min.	Max.
Limestone												
Top lysimeter	0.25	0.20	0.30	0.17	<0.01	0.33	8.3	8.0	8.45	1,640	1,500	1,760
Bottom lysimeter	0.20	0.10	0.35	1.24	0.22	2.25	12.1	11.9	12.2	3,440	1,680	4,350
Drain	0.25	< 0.10	0.30	1.01	0.64	1.55	12.1	12.0	12.2	2,640	1,640	4,170
Dolomite												
Top lysimeter	0.25	0.10	0.40	2.45	0.59	4.31	12.5	12.4	12.5	8,020	6,370	9,240
Bottom lysimeter	<0.10	< 0.10	0.15	0.76	0.33	1.19	11.9	11.2	12.3	3,870	1,640	5,370
Drain	0.25	< 0.10	0.40	0.57	0.10	1.94	12.0	11.9	12.1	2,110	1,560	3,050
Sanitary landfill												
Top lysimeter	<0.10	< 0.10	<0.10	0.68	0.57	0.79	12.2	12.1	12.2	5,040	4,500	5,980
Middle lysimeter	0.13	0.10	0.15	0.30	<0.01	0.59	12.0	11.8	12.1	3,580	3,230	3,830
Bottom lysimeter	0.30	< 0.10	0.70	0.15	<0.01	0.31	12.2	12.1	12.2	4,750	4,470	5,130
Drain	0.35	0.10	0.45	0.61	<0.01	0.84	12.1	11.7	12.4	4,480	1,820	6,300
Coal mine												
Top lysimeter	0.75	0.10	1.40	0.30	0.22	0.37	8.4	7.9	8.8	1,640	1,560	1,740
Middle lysimeter	0.25	0.10	0.30	0.30	<0.01	0.59	12.2	12.0	12.4	4,610	4,020	5,420
Bottom lysimeter	0.15	0.10	0.20	1.29	0.33	2.25	12.3	12.1	12.4	4,680	4,150	5,020
Drain	0.10	< 0.10	0.25	0.80	0.50	2.75	12.0	11.9	12.3	2,550	1,680	3,930
Ocean												
Top lysimeter	0.45	0.45	0.45	--	--	--	10.2	7.95	11.4	21,100	16,000	23,900
Drain	0.35	0.15	0.55	0.10	0.10	0.10	12.0	11.9	12.0	44,000	37,300	48,000

Continued

TABLE 68 (Continued)

Environment Test Column	Boron Avg.[f]	Boron Min.	Boron Max.	Nitrates Avg.	Nitrates Min.	Nitrates Max.	pH Avg.	pH Min.	pH Max.	Specific Conductance Avg.	Specific Conductance Min	Specific Conductance Max.
Sandy soil												
Top lysimeter	0.15	0.15	0.20	<0.01	0.01	0.01	7.2	6.9	7.5	1,390	1,300	1,440
Middle lysimeter	0.10	<0.10	0.20	1.64	0.86	2.41	7.6	7.4	7.9	1,235	1,100	1,370
Bottom lysimeter	0.10	<0.10	0.15	1.97	1.43	2.50	8.2	7.9	8.5	810	760	840
Drain	0.30	0.20	0.35	1.48	1.09	3.21	7.6	7.2	7.8	1,150	1,040	1,200
Clayey soil												
Top lysimeter	0.45	0.10	0.90	0.97	0.97	0.97	11.4	11.1	11.6	1,720	1,670	1,780
Middle lysimeter	0.20	0.20	0.25	0.64	<0.01	1.25	8.3	8.1	8.5	1,410	1,250	1,570
Bottom lysimeter	0.35	0.30	0.45	0.27	<0.01	0.53	7.55	7.3	7.8	1,910	1,850	1,970
Drain	0.65	0.55	0.70	0.58	0.55	0.70	7.8	7.0	8.1	2,320	1,560	3,900
Silty soil												
Top lysimeter	0.25	0.25	0.25	1.99	1.99	1.99	9.5	7.9	12.3	2,970	675	7,520
Middle lysimeter	0.15	0.15	0.20	0.85	0.48	1.21	10.1	8.5	12.2	2,450	405	6,460
Bottom	0.10	<0.10	0.25	0.88	0.75	1.01	11.8	11.5	12.1	1,970	800	3,540
Drain	0.45	0.15	0.65	0.09	<0.01	0.53	12.1	12.1	12.2	4,620	2,700	5,280

[a] All constituents are reported in mg/l unless otherwise noted.

[b] The value in parentheses is the permissible contamination level as presented in Tables 56 and 57.

[c] Recommended maximum concentration in irrigation waters (see Table 57).

[d] Municipal water quality criteria (see Table 56).

[e] EPA interim primary drinking water regulation (see Table 56).

[f] Avg = Includes the average of 2 to 4 analyses of monthly composites and one analysis of a four-month composite.

TABLE 69. LEACHATE ANALYSES OF THE TEST COLUMNS FROM THE ESBM

Environment Test Column	Aluminum (5.0 mg/l)[a,b,c]			Cadmium (0.01 mg/l)[d]			Calcium (no criteria)			Copper (1.0 mg/l)[d]			Mercury (0.005 mg/l)[e]		
	Avg.[f]	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Limestone															
Top lysimeter	0.25	0.10	0.40	0.01	<0.01	0.03	135	98	205	0.02	<0.01	0.03	-	--	--
Bottom lysimeter	0.24	<0.02	0.70	<0.01	<0.01	<0.01	234	160	282	<0.01	<0.01	<0.01	0.0011	0.0003	0.0019
Drain	3.25	0.10	5.80	<0.01	<0.01	0.01	236	113	498	<0.01	<0.01	0.01	0.0009	0.0005	0.0028
Dolomite															
Top lysimeter	0.20	0.20	0.20	<0.01	<0.01	0.02	203	80	350	<0.01	<0.01	0.02	0.0008	0.0008	0.0008
Bottom lysimeter	0.23	0.20	0.30	<0.01	<0.01	0.02	162	50	290	<0.01	<0.01	0.02	0.0014	0.0008	0.0020
Drain	1.27	1.10	1.60	<0.01	<0.01	0.01	317	65	600	<0.01	<0.01	0.01	0.0010	0.0005	0.0033
Sanitary landfill															
Top lysimeter	0.65	0.20	1.20	<0.01	<0.01	0.01	391	155	685	<0.01	<0.01	0.01	0.0031	0.0030	0.0032
Middle lysimeter	0.35	0.10	0.60	<0.01	<0.01	0.01	285	63	705	<0.01	<0.01	0.01	0.0008	0.0008	0.0008
Bottom lysimeter	0.38	0.30	0.60	<0.01	<0.01	0.01	270	147	380	<0.01	<0.01	0.01	0.0025	0.0024	0.0025
Drain	1.70	1.10	3.10	<0.01	<0.01	<0.01	399	267	500	<0.01	<0.01	<0.01	0.0033	0.0005	0.0106
Coal mine															
Top lysimeter	0.17	<0.02	0.30	<0.01	<0.01	0.03	335	180	550	<0.01	<0.01	0.03	0.0010	0.0007	0.0013
Middle lysimeter	0.50	0.10	0.70	<0.01	<0.01	0.01	346	202	570	<0.01	<0.01	0.01	0.0009	0.0008	0.0009
Bottom lysimeter	0.24	0.10	0.50	<0.01	<0.01	0.01	219	107	300	<0.01	<0.01	0.01	0.0014	0.0007	0.0027
Drain	2.68	0.40	3.79	<0.01	<0.01	0.01	240	105	550	<0.01	<0.01	0.01	0.0005	0.0003	0.0008
Ocean															
Top lysimeter	0.23	0.10	0.40	0.08	0.07	0.09	1,836	1,347	2,325	0.07	0.05	0.09	0.0022	0.0009	0.0035
Drain	0.28	0.18	0.50	0.13	0.04	0.17	1,986	1,540	3,400	0.13	0.04	0.17	0.0042	0.0002	0.0026

Continued

TABLE 69 (Continued)

Environment Test Column	Aluminum			Cadmium			Calcium			Copper			Mercury		
	Avg.^{f}	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Sandy soil															
Top lysimeter	0.60	0.10	1.60	<0.01	<0.01	0.01	133	80	170	<0.01	<0.01	0.01	--	--	--
Middle lysimeter	0.63	0.20	0.90	<0.01	<0.01	0.01	236	80	360	<0.01	<0.01	0.01	0.0012	0.0006	0.0024
Bottom lysimeter	0.25	<0.02	0.50	0.01	<0.01	0.03	158	127	192	0.01	<0.01	0.03	0.0009	0.0007	0.0012
Drain	0.46	<0.02	0.72	<0.01	<0.01	0.03	112	82	170	<0.01	<0.01	0.03	0.0013	0.0007	0.0016
Clayey soil															
Top lysimeter	0.18	<0.02	0.40	<0.01	<0.01	0.01	291	95	460	<0.01	<0.01	0.01	0.0014	0.0006	0.0022
Middle lysimeter	0.48	<0.02	1.80	<0.01	<0.01	0.01	349	217	460	<0.01	<0.01	0.01	0.0055	0.0007	0.0083
Bottom lysimeter	0.10	<0.02	0.20	0.01	<0.01	0.02	456	185	800	0.01	<0.01	0.01	0.0014	0.0012	0.0116
Drain	2.49	0.20	4.10	<0.01	<0.01	0.02	307	144	750	<0.01	<0.01	0.03	0.0009	0.0005	0.0024
Silty soil															
Top lysimeter	0.20	0.20	0.20	<0.01	<0.01	0.02	231	122	340	<0.01	<0.01	0.01	0.0012	0.0008	0.0016
Middle lysimeter	0.25	0.20	0.30	<0.01	<0.01	0.01	258	70	565	<0.01	<0.01	0.01	0.0012	0.0009	0.0014
Bottom lysimeter	0.30	0.30	0.30	<0.01	<0.01	0.01	247	40	645	0.01	<0.01	0.02	0.0008	0.0005	0.0010
Drain	1.08	0.30	1.35	<0.01	<0.01	0.03	524	448	700	<0.01	<0.01	0.03	0.0009	0.0005	0.0033

Continued

TABLE 69 (Continued)

Environment Test Column	Boron (1.0 mg/l)[d]			Nitrate as Nitrogen[e] (10 mg/l as N)			pH[d] (6.0 to 8.5)			Specific Conductance (μ mhos)		
	Avg.[f]	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Limestone												
Top lysimeter	0.20	0.10	0.25	0.28	<0.01	0.57	8.4	8.0	8.7	750	515	960
Bottom lysimeter	<0.10	<0.10	0.10	0.22	<0.01	0.44	12.1	12.0	12.2	2,795	1,750	3,540
Drain	3.20	<0.10	5.50	0.39	<0.01	1.99	12.2	12.1	12.4	2,880	1,800	4,830
Dolomite												
Top lysimeter	0.15	0.10	0.20	1.98	0.19	3.76	10.3	8.3	12.3	5,180	5,180	5,180
Bottom lysimeter	0.35	0.20	0.50	0.66	0.44	0.88	9.9	8.7	12.2	404	370	439
Drain	0.20	<0.10	0.25	1.32	0.04	7.54	12.3	12.1	12.4	4,750	2,740	5,640
Sanitary landfill												
Top lysimeter	0.15	<0.10	0.35	0.27	<0.01	0.53	12.0	11.8	12.4	3,540	1,630	6,930
Middle lysimeter	0.10	<0.10	0.15	2.44	0.50	4.38	9.4	7.5	12.4	2,600	560	6,580
Bottom lysimeter	0.10	<0.10	0.15	1.00	<0.01	1.99	9.5	7.9	12.0	1,850	765	4,000
Drain	1.35	0.10	2.05	0.29	<0.01	0.36	12.3	11.9	12.4	5,060	3,280	6,000
Coal mine												
Top lysimeter	0.15	0.10	0.20	0.22	<0.01	0.44	12.0	11.2	12.5	2,760	670	5,160
Middle lysimeter	<0.10	<0.10	<0.10	1.39	0.57	2.21	12.6	12.4	12.9	4,890	4,340	5,450
Bottom lysimeter	0.10	<0.10	0.15	1.65	0.98	2.32	12.0	12.0	12.1	2,840	1,930	3,780
Drain	0.20	<0.10	0.25	1.05	0.33	1.77	12.1	12.0	12.4	2,760	1,690	4,490
Ocean												
Top lysimeter	0.75	0.35	1.15	--	--	--	11.7	10.9	12.2	33,100	28,500	35,200
Drain	0.25	0.15	0.53	0.14	0.14	0.14	11.6	11.3	12.0	37,400	36,000	40,700

Continued

TABLE 69 (Continued)

Environment Test Column	Boron Avg.[f]	Boron Min.	Boron Max.	Nitrates Avg.	Nitrates Min.	Nitrates Max.	pH Avg.	pH Min.	pH Max.	Specific Conductance Avg.	Specific Conductance Min	Specific Conductance Max.
Sandy soil												
Top lysimeter	0.25	0.10	0.55	< 0.01	< 0.01	< 0.01	11.3	10.9	11.6	950	680	1,210
Middle lysimeter	0.30	0.15	0.40	2.39	0.81	3.96	11.5	11.3	11.8	1,410	1,170	1,800
Bottom lysimeter	0.20	0.15	0.20	0.35	0.01	0.70	9.2	7.0	11.4	1,080	840	1,440
Drain	<0.10	<0.10	0.20	1.08	1.06	1.10	7.4	6.9	7.6	950	750	1,080
Clayey soil												
Top lysimeter	0.20	0.10	0.35	2.11	1.72	2.50	9.15	7.3	12.0	1,960	860	4,140
Middle lysimeter	0.45	0.15	1.00	1.34	1.34	1.34	9.0	7.8	10.8	1,820	1,450	2,560
Bottom lysimeter	0.20	0.20	0.25	1.10	1.10	1.10	8.3	7.3	9.1	2,020	1,415	2,670
Drain	0.80	0.15	1.20	0.94	0.89	1.12	9.1	8.7	9.3	2,120	1,490	3,380
Silty soil												
Top lysimeter	0.12	0.10	0.15	< 0.01	< 0.01	< 0.01	9.4	7.8	12.2	2,920	1,080	4,760
Middle lysimeter	0.14	0.14	0.14	< 0.01	< 0.01	< 0.01	9.35	7.7	12.4	4,000	1,170	6,830
Bottom lysimeter	0.10	<0.10	0.15	0.64	0.19	1.08	9.65	8.3	12.3	2,860	485	7,440
Drain	0.60	<0.10	1.00	0.85	< 0.01	4.43	12.3	12.3	12.4	6,510	5,300	7,080

[a] All constituents are reported in mg/l unless otherwise noted.

[b] The value in parentheses is the permissible contamination level as presented in Tables 56 and 57.

[c] Recommended maximum concentration in irrigation waters (see Table 57).

[d] Municipal water quality criteria (see Table 56).

[e] EPA interim primary drinking water regulation (see Table 56).

[f] Avg =Includes the average of 2 to 4 analyses of monthly composites and one analysis of a four-month composite.

TABLE 70 . LEACHATE ANALYSES OF THE TEST COLUMNS[a]

Drain Leachate from Test Column	Chemical Oxygen Demand (no criteria)[b] Avg.[d]	Min.	Max.	Total Organic Carbon (no criteria) Avg.	Min.	Max.	Total Dissolved Solids (500 mg/l)[c] Avg.	Min.	Max.
NJFA									
Limestone	16	< 10	46	6	4	8	1,375	1,144	1,740
Dolomite	< 10	< 10	40	8	5	11	2,081	1,318	2,348
Sanitary landfill	28	< 10	47	392	45	238	777	758	786
Coal mine	< 10	< 10	12	4	2	7	932	490	1,250
Ocean	<250	<250	510	8	6	10	36,884	33,585	38,092
NJSBM									
Limestone	30	< 10	113	24	24	24	1,040	664	2,170
Dolomite	22	< 10	68	14	13	14	1,671	1,120	2,920
Sanitary landfill	212	< 10	345	159	70	248	1,528	700	1,722
Coal mine	20	< 10	49	7	4	10	1,033	310	1,310
Ocean	250	<250	490	7	4	10	37,234	32,440	38,552
VFA									
Limestone	14	< 10	61	7	4	10	557	270	667
Dolomite	< 10	< 10	< 10	5	2	8	390	340	551
Sanitary landfill	30	< 10	115	126	58	195	535	482	820
Coal mine	15	< 10	84	8	3	14	633	365	1,160
Ocean	296	<250	504	22	2	43	34,397	31,538	36,256
VSBM									
Limestone	20	< 10	55	14	8	20	667	450	754
Dolomite	22	< 10	61	12	9	14	915	642	2,065
Sanitary landfill	28	< 10	47	216	59	374	1,198	946	1,578
Coal mine	28	< 10	40	19	17	21	1,345	330	1,674
Ocean	<250	<250	<250	29	19	39	40,167	33,500	43,948
EFA									
Limestone	24	< 10	39	22	16	27	690	352	1,440
Dolomite	18	< 10	27	15	12	18	563	380	1,150
Sanitary landfill	234	147	418	138	127	150	2,122	1,090	2,810
Coal mine	11	< 10	16	47	14	80	845	720	1,345
Ocean	<250	< 25	345	8	8	9	35,778	34,304	36,348
Sandy soil	83	< 10	110	279	210	318	352	444	630
Clayey soil	< 10	< 10	< 10	58	22	93	1,309	574	4,250
Silty soil	46	29	76	42	24	59	929	795	962

(Continued)

TABLE 70 (Continued)

Drain Leachate from Test Column	Chemical Oxygen Demand (no criteria)[b]			Total Organic Carbon (no criteria)			Total Dissolved Solids (500 mg/l)[c]		
	Avg.[d]	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
ESBM									
Limestone	28	< 10	42	8	6	10	769	574	1,270
Dolomite	26	< 10	67	8	4	12	1,183	980	1,232
Sanitary landfill	221	169	357	110	81	138	1,393	1,100	1,568
Coal mine	35	< 10	55	12	10	15	394	172	945
Ocean	<250	<250	347	9	8	10	37,574	33,760	39,790
Sandy soil	90	64	182	76	3	149	500	422	660
Clayey soil	354	120	929	86	85	87	1,587	1,298	2,440
Silty soil	68	44	122	48	32	63	1,382	1,380	1,382

[a] All constituents are reported in mg/l.

[b] The value in parentheses is the permissible contamination level as presented in Table 56 .

[c] Municipal water quality criteria.

[d] Avg = Includes the average of 2 to 4 analyses of monthly composites and one analysis of a four-month composite.

The municipal water quality criteria for copper was not exceeded. Most levels of copper found in the leachates were less than 0.02 mg/l. The Environmental Protection Agency primary drinking water maximum contaminant levels for mercury and nitrate were not exceeded. The boron water quality criteria level was generally not exceeded. Only the NJFA, NJSBM, and the ESBM leachates from the sanitary landfill, coal mine, and limestone, respectively, average concentrations higher than 2.0 mg/l.

The leachates generally were more basic than the recommended optimum pH range of 6.0 to 8.5. Only the NJFA, and VFA, residues resulted in leachates which come within the recommended pH ranges. The recommended limits for total dissolved solids of 500 mg/l was generally exceeded; however, the total dissolved solids usually did not exceed the concentration of 1,000 mg/l.

The following paragraphs further evaluate the data presented in Tables 64 through 70. In the discussion, those constituents which generally decreased in concentration after percolating from the top lysimeter leachate to the drain leachate were considered to have been attenuated, or retained, in the columns' environment. Conversely, the constituents, which generally increased in concentration with passage through the test columns were considered to have been readily leached from the in-situ media.

For the NJFA test columns, as shown in Table 64, aluminum readily leached through the dolomite, sanitary landfill and the ocean column simulated environments; an average of 0.08 mg/l cadmium and copper were found in the ocean column environment, whereas all the other columns' environments showed more than 0.02 mg/l; boron was readily leached from the sanitary landfill, coal mine, and ocean columns' environments; nitrates, in the limestone quarry column environments was readily leached, while the ocean column environment showed a retention of nitrates; there appeared to be no other significant differences.

The Table 65 results from the NJSBM column leachates showed that aluminum was readily leached from the ocean column environment; cadmium and copper averaged about 0.8 mg/l in the ocean column environment, while the other columns simulated environments contained no more than 0.02 mg/l; calcium was retained in the limestone, dolomite, and the sanitary landfill columns simulated environments; boron was readily leached from the coal mine and ocean columns' environments; the pH of the leachate increased in the limestone and coal mine columns' environments and decreased in the sanitary landfill column environment leachates. The specific conductance decreased in the limestone, dolomite, and sanitary landfill columns' environments, and increased in the coal mine column environment leachate. No other significant trends were apparent.

The VFA leachate results shown in Table 66, showed that aluminum was readily leached from the sanitary landfill column environment; the ocean column environment averaged about 0.8 mg/l cadmium and copper; cadmium was held in the dolomite and ocean columns' environments; boron was attenuated in the sanitary landfill columns and readily leached from the ocean environment columns; the nitrate concentration decreased rapidly on the applied wastes which passed through the dolomite sanitary landfill columns, and coal mine column environments; only the limestone column environment showed any change in the leachate pH, that is, the pH increased from 8.7 to 11.3 as the water percolated through the test column; no other significant differences were observed.

For the VSBM test columns, as shown in Table 67, the cadmium and copper concentration in the ocean leachate columns averaged about 0.7 mg/l; calcium in the sanitary landfill and the ocean column simulated environments was readily leached while the limestone column environment attenuated the calcium; boron leached through all but the ocean column environment; the nitrate was attenuated in the limestone column environment; the leachate Ph decreased in the limestone column environment and increased in the dolomite column environment, and the specific conductance decreased in the limestone column environment and increased in the sanitary landfill column environment.

The EFA residue as shown in Table 68, indicated the following leachate effluent chemical characteristics: aluminum was leached from the dolomite, clayey soil, and the silty soil columns' simulated environments; the dolomite, sandy soil, and clayey soil columns' environments attenuated the calcium and the ocean columns' environments' leachate contained about 0.06 mg/l cadmium and copper; the coal mine test column attenuated the boron; nitrate was readily leached from the limestone, clayey soil, and silty soil test columns, while nitrate was retained by the dolomite test column simulated environment; the leachate pH increased with passage through the limestone and silty soil test columns' simulated environments and decreased while passing through the coal mine and the clayey soil test columns; the specific conductance decreased from 8,020 to 2,110 mhos after passing through the dolomite test column environment; no other significant trends were noted.

The ESBM leachate, as shown in Table 69, showed the following trends: aluminum was readily leached from the sanitary landfill, the coal mine, and the clayey and silty soil test columns' simulated environments; cadmium and copper averaged about 0.12 mg/l in the ocean leachate; boron was readily leached from all the test columns' simulated environments, except the dolomite quarry and sandy soil; nitrates were retained in the clayey soil test columns, while nitrates were leached by the coal mine and the silty soil test columns' simulated environments; the pH decreased in the sandy soil column environments and increased in the limestone, dolomite, and the silty soil columns' simulated environments as the water leached through the test columns; and an increase in the specific conductance occurred as the applied water passed through the limestone and silty soil test columns. There were no other apparent significant differences or trends.

The results found in Table 70 show the following differences. The COD was significantly higher, above 200 mg/l, in the sanitary landfill column leachates coming from the NJSBM, EFA, and ESBM residues, and in the clayey soil column leachate percolating from the ESBM residue. The ocean simulated environment, of course, was high in COD because of the highly saline sea water. Generally, all the other column leachates averaged less than 50 mg/l chemical oxygen demand (COD). Likewise, the sanitary landfill column leachate showed significantly higher total organic carbon (TOC), from 110 to 392 mg/l, for all the residues. The ESBM leachate passing through the sandy, clayey, and silty soil columns' environments ranged from 48 to 86 mg/l. All other TOC results were generally lower than 20 mg/l. The VFA leachate had the lowest total dissolved solids than any of the other residues, ranging from 390 to 633 mg/l.

CHAPTER 8

COMPARISON OF THE RESIDUE CHARACTERIZATION AND LEACHING METHODS

An outcome of the fluidized-bed residue characterization (Chapter 5: Tables 13 to 17) and the pilot test column study (Chapter 6: Tables 44 to 49) was that the studies provided four basically different methods for determining the leaching characteristics of the residue material. The four procedures are described below:

1. Total Residue Digestion: a sample of the residue was digested in perchloric acid and the subsequent digestate was analyzed.

2. Soluble Salt Extraction: after the addition of distilled water, 1.0 N hydrochloric acid, or 1.0 N sodium hydroxide, the residue sample was shaken for 24 hours and filtered; the resultant filtrate was analyzed for soluble content.

3. Residue Leaching Test: water was passed through a sample of the residue packed in a 5 cm 10 by 30 cm high column, and the resulting leachate was analyzed. (See Figures 5 to 7).

4. Pilot Column Leaching Test: a sample of the residue was placed onto layers of stratum material contained in a larger (20.3 cm diameter x 3 m depth) column; and the leachate, after passing through the simulated environment, was analyzed.

The results obtained from the four different procedures are shown in Tables 71 to 76. The values for the Pilot Column Leaching Test were calculated by multiplying the average concentrations, in mg/l (see Tables 44 to 49) by the total volumes of water applied to the test columns, in liters, and by dividing these results by the total kg residue added to the columns. A comparison of the methods indicate that no two procedures gave similar results. The total residue digestion generally resulted in much higher concentration levels. In particular, the concentrations of aluminum, copper, iron, manganese, and potassium found in the digestate were almost always 100 to 1,000 times greater than the constituent content found in any of the leaching processes. Magnesium showed similar characteristics for VSBM, EFA, and ESBM; however, the base soluble extract of NSFA and NJSBM and the acid soluble extract of VFA gave results which were no lower than one-half the concentration found in the digested sample. Calcium was not determined by total digestion; however, apparently the total content of calcium (3 to 7 percent) was extracted from acid soluble fraction. The total residue digestion procedure generally resulted in concentrations much higher than those found in any leaching method because the digestion broke down the solid residue into an entirely soluble form; therefore, this method was not suitable for evaluating the potential leaching characteristics of residues on the natural environment.

The results from the soluble salt extraction procedure (i.e., the shake test) have been used to equate the potential impact of residues and other materials on disposal sites. For some constituents, particularly those which are highly ionic (for example, potassium, sodium and chloride), the extraction process may approximate the concentration levels found in the leachate from an actual disposal site; however, this study showed that there was no

TABLE 71. COMPARISON OF FOUR METHODS FOR DETERMINING THE LEACHING CHARACTERISTICS OF NJFA

Constituent	mg Constituent/kg Residue									
	Total Residue Digestion	Soluble Salt Extraction			Residue Leaching Test[a]	Pilot Column Leaching Test[b]				
		Water Soluble	Acid Soluble	Base Soluble		Limestone Quarry	Dolomite Quarry	Sanitary Landfill	Coal Mine	Ocean Disposal
Chloride	--	< 5	< 5	6	800	300	290	200	340	--
Sulfate	53,600	1,190	5,300	26,000	30,850	14,450	10,600	2,350	14,900	11,350
Aluminum	5,800	--	--	--	--	--	--	--	--	--
Arsenic	0.2	< 0.1	--	--	--	--	--	--	--	--
Cadmium	2.8	< 0.1	0.2	0.2	--	--	--	--	--	--
Calcium	--	1,805	34,600	< 10	3,520	--	--	--	--	--
Copper	--	--	--	--	--	--	--	--	--	--
Iron	11,030	<1.0	78	1.6	--	1.3	1.9	--	1.9	0.6
Lead	40	2.5	7.7	6.0	2.8	1.3	1.4	0.8	2.6	1.4
Magnesium	6,290	10	< 1.0	2,360	--	--	--	--	--	--
Manganese	650	--	--	--	--	--	--	--	--	--
Nickel	--	--	--	--	--	0.9	0.3	0.2	0.8	0.3
Potassium	7,200	24	440	--	--	--	--	--	--	--
Sodium	80	22	--	--	--	--	--	--	--	--
Zinc	92	< 0.2	8.0	0.5	--	1.8	1.3	0.7	1.6	6.1

[a] These values were the results after a ratio of 18.4 liters of water (or sea water) per kilogram of residue were passed through the columns. The concentrations of the constituents would increase with increasing water addition.

[b] The results were for the drain leachate.

TABLE 72. COMPARISON OF FOUR METHODS FOR DETERMINING THE LEACHING CHARACTERISTICS OF NJSBM

Constituent	mg Constituent/kg Residue									
	Total Residue Digestion	Soluble Salt Extraction			Residue Leaching Test[a]	Pilot Column Leaching Test[b]				
		Water Soluble	Acid Soluble	Base Soluble		Limestone Quarry	Dolomite Quarry	Sanitary Landfill	Coal Mine	Ocean Disposal
Chloride	--	< 5	< 5	8	700	875	700	575	350	--
Sulfate	--	1,900	1,000	17,400	35,070	7,460	8,140	2,125	6,335	9,920
Aluminum	960	0.06	0.26	< 1.0	--	--	--	--	--	--
Arsenic	--	--	--	--	--	--	--	--	--	--
Cadmium	4.0	< 1.0	0.5	0.2	--	--	--	--	--	--
Calcium	--	6,010	96,750	< 10	8,700	--	--	--	--	--
Copper	168	0.5	1.1	0.12	--	--	--	--	--	--
Iron	1,830	< 1.0	7.6	1.8	--	0.6	1.0	--	0.90	1.2
Lead	32	2.4	1.4	5.9	5.0	1.4	1.7	2.7	2.4	1.8
Magnesium	2,530	95	< 10	3,200	--	--	--	--	--	--
Manganese	475	0.02	0.95	< 0.02	--	--	--	--	--	--
Nickel	--	0.5	7.7	0.75	--	0.3	0.4	0.4	1.2	0.2
Potassium	5,600	32	32	248	--	--	--	--	--	--
Sodium	72	89	<1.0	--	--	--	--	--	--	--
Zinc	92	< 0.2	1.0	0.2	0.8	1.0	2.0	0.8	1.0	1.8

[a] These values were the results after a ratio of 25.0 liters of water (or sea water) per kilogram of residue were passed through the columns. The concentration of the constituents would increase with increasing water addition.

[b] The results were for the drain leachate.

TABLE **73**. COMPARISON OF FOUR METHODS FOR DETERMINING THE LEACHING CHARACTERISTICS OF VFA

Constituent	mg Constituent/kg Residue									
	Total Residue Digestion	Soluble Salt Extraction			Residue Leaching Test[a]	Pilot Column Leaching Test [b]				
		Water Soluble	Acid Soluble	Base Soluble		Limestone Quarry	Dolomite Quarry	Sanitary Landfill	Coal Mine	Ocean Disposal
Chloride	--	ND[c]	ND	6	850	385	330	455	680	--
Sulfate	--	1,600	1,050	17,400	33,000	15,620	7,925	1,475	19,100	24,000
Aluminum	3,600	ND	1.2	ND	--	--	--	--	--	--
Arsenic	<0.1	--	--	--	--	--	--	--	--	--
Cadmium	0.8	ND	0.5	0.2	--	--	--	--	--	--
Calcium	--	540	32,000	ND	10,300	--	--	--	--	--
Copper	164	0.02	0.92	ND	--	--	--	--	--	--
Iron	7,390	0.5	11.0	1.7	1.9	1.6	1.0	--	1.2	0.8
Lead	20	1.6	1.3	7.1	5.6	2.0	1.1	1.6	6.9	1.7
Magnesium	3,000	96	1,940	10	--	--	--	--	--	--
Manganese	165	0.02	0.87	ND	--	--	--	--	--	--
Nickel	--	0.25	7.7	ND	--	0.4	0.4	0.6	0.9	1.0
Potassium	8,400	33	276	--	--	--	--	--	--	--
Sodium	112	145	ND	--	--	--	--	--	--	--
Zinc	80	0.08	1.1	1.0	0.83	1.7	0.7	1.2	2.6	2.3

[a] These values were the results after a ratio of 27.6 liters of water (or sea water) per kilogram of residue were passed through the columns. The concentration of the constituents would increase with increasing water addition.

[b] The results were for the drain leachate.

[c] ND - not detected.

TABLE **74**. COMPARISON OF FOUR METHODS FOR DETERMINING THE LEACHING CHARACTERISTICS OF VSBM

	mg Constituent/kg Residue									
		Soluble Salt Extraction				Pilot Column Leaching Test[b]				
Constituent	Total Residue Digestion	Water Soluble	Acid Soluble	Base Soluble	Residue Leaching Test[a]	Limestone Quarry	Dolomite Quarry	Sanitary Landfill	Coal Mine	Ocean Disposal
Chloride	--	ND[c]	ND	23	500	215	145	350	450	--
Sulfate	12,200	1,640	1,050	32,500	27,850	7,250	3,950	4,580	5,800	6,780
Aluminum	3,840	0.06	0.26	ND	--	--	--	--	--	--
Arsenic	0.3	--	--	--	--	--	--	--	--	--
Cadmium	2.4	ND	0.5	0.3	--	--	--	--	--	--
Calcium	--	750	32,000	ND	6,900	--	--	--	--	--
Copper	225	0.5	1.07	0.12	--	--	--	--	--	--
Iron	4,070	0.1	6.6	2.2	1.4	0.7	0.4	--	0.2	0.6
Lead	28	1.1	1.5	7.6	4.9	1.2	0.4	1.9	1.6	1.3
Magnesium	585	22	22	ND	--	--	--	--	--	--
Manganese	315	0.02	0.95	ND	--	--	--	--	--	--
Nickel	--	0.5	7.7	0.75	--	0.07	0.07	0.15	0.4	0.3
Potassium	19,400	6.3	276	--	--	--	--	--	--	--
Sodium	192	178	100	--	--	--	--	--	--	--
Zinc	208	ND	0.3	0.4	0.55	--	--	--	--	--

[a] These values were the results after a ratio of 18.4 liters of water (or sea water) per kilogram of residue were passed through the columns. The concentration of the constituents would increase with increasing water addition.

[b] The results were for the drain leachate.

[c] ND - not detected.

TABLE **75.** COMPARISON OF FOUR METHODS FOR DETERMINING THE LEACHING CHARACTERISTICS OF EFA

Constituent	mg Constituent/kg Residue									
	Total Residue Digestion	Soluble Salt Extraction			Residue Leaching Test[a]	Pilot Column Leaching Test[b]				
		Water Soluble	Acid Soluble	Base Soluble		Limestone Quarry	Dolomite Quarry	Sanitary Landfill	Coal Mine	Ocean Disposal
Chloride	--	11,200	5,000	10,000	6,850	1,000	3,800	1,525	780	--
Sulfate	--	4,380	2,625	24,310	30,000	10,850	7,300	17,360	8,500	7,200
Aluminum	240	0.25	1.75	ND	--	--	--	--	--	--
Arsenic	ND[c]	ND	0.05	ND	--	--	--	--	--	--
Cadmium	1.6	ND	0.08	0.05	--	--	--	--	--	--
Calcium	--	4,500	70,000	315	--	--	--	--	--	--
Copper	180	ND	2.2	ND	--	--	--	--	--	--
Iron	48	1.0	7.0	0.2	6.3	1.1	1.0	--	0.4	1.4
Lead	24	0.08	ND	ND	4.4	4.0	2.5	6.0	3.0	2.0
Magnesium	375	1.0	1.3	1.0	--	--	--	--	--	--
Manganese	120	0.08	0.75	0.03	--	--	--	--	--	--
Nickel	--	1.2	8.0	1.5	18	1.0	1.6	0.8	0.6	1.1
Potassium	6,000	50	232	--	--	--	--	--	--	--
Sodium	--	245	270	--	--	--	--	--	--	--
Zinc	32	0.15	0.3	0.02	0.75	1.4	1.0	0.3	1.5	1.2

[a] These values were the results after a ratio of 22.0 liters of water (or sea water) per kilogram of residue were passed through the columns. The concentration of the constituents would increase with increasing water addition.

[b] The results were for the drain leachate.

[c] ND - not detected.

TABLE 76. COMPARISON OF FOUR METHODS FOR DETERMINING THE LEACHING CHARACTERISTICS OF ESBM

Constituent	mg Constituent/kg Residue									
	Total Residue Digestion	Soluble Salt Extraction			Residue Leaching Test[a]	Pilot Column Leaching Test[b]				
		Water Soluble	Acid Soluble	Base Soluble		Limestone Quarry	Dolomite Quarry	Sanitary Landfill	Coal Mine	Ocean Disposal
Chloride	--	8,200	12,500	10,280	6,100	5,350	4,700	2,600	2,750	--
Sulfate	--	3,380	250	4,625	54,000	15,300	9,700	22,300	7,300	18,000
Aluminum	--	0.25	1.25	1.0	--	--	--	--	--	--
Arsenic	0.4	ND[c]	0.1	ND	--	--	--	--	--	--
Cadmium	2.4	0.05	0.28	ND	--	--	--	--	--	--
Calcium	--	4,750	75,000	60	--	--	--	--	--	--
Copper	148	0.5	2.0	ND	--	--	--	--	--	--
Iron	ND	1.7	6.0	ND	8.2	3.2	2.2	--	3.2	1.8
Lead	16	0.17	ND	ND	7.9	15.6	16.8	11.4	6.9	14.8
Magnesium	1,895	1.0	1.3	1.0	--	--	--	--	--	--
Manganese	215	0,1	0.6	ND	--	--	--	--	--	--
Nickel	--	0.25	7.5	ND	54	1.7	2.5	1.3	1.1	2.4
Potassium	11,400	ND	ND	--	--	--	--	--	--	--
Sodium	144	40	45	--	--	--	--	--	--	--
Zinc	28	0.15	0.30	ND	0.78	9.6	5.5	4.1	3.8	10.6

[a] These values were the results after a ratio of 39.4 liters of water (or sea water) per kilogram of residue were passed through the columns. The concentration of the constituents would increase with increasing water addition.

[b] The results were for the drain leachate.

[c] ND - not detected.

consistent relationship between the constituent levels found in the soluble salt extracts and those found in the leachate from the residue or the pilot column leaching tests. The chloride concentrations found in the soluble salt extracts of the NJFA, NJSBM, VFA, and VSBM were almost neglible compared to the concentration levels (greater than 100 mg/kg residue) found in the leachate from the residue and the pilot column tests. On the other hand, the soluble salt extracts from Esso, Great Britain residues generally contained higher chloride concentrations than the pilot column leachate samples. Furthermore, the sulfate, iron, and zinc concentrations were almost always less in the water soluble portion of the extracts. The water soluble extructs of lead and nickel more nearly approximated the constituents' concentration found in the pilot column leaching test.

The residue leaching test almost always resulted in higher constituent concentration (the only exception was zinc) when compared with the values found in the pilot column leaching test. This was not unexpected because, although both methods leached constituents with passage of water through a column, the leachate in the larger pilot-scale test column passed through additional layers of stratum material. Thus, less bypassing occurred which resulted in lower leachate concentrations.

In summary, the total residue digestion method did not relate directly to the leaching characteristics of the fluidized-bed residues. The analytical data obtained from the soluble salt extractions generally did not approximate the results found by the pilot test column leaching test; most of the results from the extractions showed lower concentrations, sometimes the chloride concentrations were greater, and rarely did the analytical results compare favorably with the pilot test column leachate results. The residue leaching test proved to give results that were greater in concentrations than those found in the pilot column leaching tests. No two procedures gave similar results; and consequently, since the pilot test columns study provided percolation of the residues' leachate through subsurface materials, the analytical data from the pilot column leaching test appears to most effectively predict the potential leaching impacts of residues on the natural environment.

CHAPTER 9

RECOVERY POTENTIAL FOR FLUIDIZED-BED RESIDUES

Introduction

Coal combustion has generated large quantities of residues. In 1972, for example, approximately 30 million kkg of coal residues were produced. Residue quantities were projected to increase substantially during the period 1970-90, primarily as a result of increased power demand. During that period, the electric utility industry was predicted to increase its consumption of coal by 100 percent and of oil by 150 percent.[54] Residue quantities are likely to increase more than proportionately for several reasons. First, as supplies of low-ash fuel are depleted, greater use will be made of higher-ash fuels. Second, more stringent pollution control regulations will necessitate less discharge to the environment; consequently, the more efficient fluidized-bed plants may be favored over conventional coal combustion and oil gasification processes. Third, fluidized-bed coal combustion and oil gasification methods may be adopted by a significant portion of the industry. Both the once-through and the regenerative limestone/dolomite fluidized-bed systems have generated substantially more residues than conventional systems, although the increase has been greatest with once-through systems. Preliminary work suggests that once-through systems are favored by current economics: the projected expense of regeneration (less the value of recovered sulfur products) appeared to be greater than the saving from reduced limestone consumption. For coal boilers, once-through fluidized-bed systems should generate a minimum of 50 percent more residues than do conventional coal-fired power plants.[54]

This chapter discusses possible residue application areas and the market prospects for fluidized-bed residues. The following topics were considered:

- Overall recovery prospects for fluidized-bed residues.
- Review of the applications for conventional coal ash and lime/limestone wet scrubber residues.
- Evaluation of specific, feasible reclamation applications of residues in concrete, asphalt, agriculture (soil amendment), soil cover (strip mines and landfills), soil cement, pozzolan cements (lime-fly ash-aggregate and lime-cement-fly ash aggregate), acid mine drainage treatment, and road ice control.
- Preliminary assessment of market potential for residue applications.

Overall Reuse Prospects

The history of reclaiming conventional coal ash provided an insight into what the utilization prospects for fluidized-bed residues might be. Relatively little of the conventional ash generated has found its way into productive use. Until about 1968, the ash utilization rate had been increasing rapidly, moving from 2 percent in 1955 to 17.5 percent in 1968.[70] Since then, however, the rate has remained relatively constant, although in total quantities reuse has continued to increase. The utilization rate has remained low even though many technically sound applications have been developed which could potentially absorb more than the annual quantities generated.[53] Table 77 presents the estimated maximum, technically feasible, utilization potentials. Although many reuse applications exist, it is not likely that the utilization rate will consume the available supply in the near future because of the following reasons:

- Technical complexity of the application. Potential users are less likely to adopt a new residue material if it is significantly more complicated, or if it requires major changes in production methods.
- Reliability of the new raw residue process or product.
- Sufficient information about the potential application.
- Existence of a reliable source of supply for residues or residue-based products.
- Uniformity and quality of the residue or residue-based product.

Many of these barriers may be overcome in time, but unless further recovery incentives are provided, most of the increased residues will not be reclaimed and, instead, will require disposal. This conclusion must be modified for fluidized-bed residues, however, since their composition and characteristics are substantially different from those of conventional combustion ash residues. This is illustrated in Tables 78 and 79 , which compare the composition of conventional coal ash, modified ash (MFA), and fluidized-bed ash. The lime or dolomite modified fly ash was generated by flue gas desulfurization (FGD) systems (e.g., wet limestone scrubbers) and fluidized-bed combustors. Since diffences affect the suitability of a residue for a given application, it is difficult to predict the potential successes or failures of FBC residue applications. The FGD residues (particularly those from dry systems) were quite similar to fluidized-bed residues; hence, the recovery potential of FGD and fluidized-bed residues may be compared with some reliability.

Provided that suitable reclaimable materials are available, a potential user's decision will be based on the relative prices of conventional and residue materials, transportation, and necessary preprocessing of the residues over that required for the competing conventional material. A potential user will use materials which reduce his production costs and maintain desired product quality.

There has been considerable literature published on applications and potential uses for residues from conventional coal combustion, municipal waste incineration, and lime-limestone scrubbing used for air pollution control on high sulfur fossil fuel units. These are summarized in the following sections.

Types of Coal Ash

There are three types of residues collected from coal combustion: fly ash, bottom ash, and slag. Fly ash is the ash collected from the stack effluent; bottom ash and slag are the

TABLE 77 . ESTIMATED ASH UTILIZATION POTENTIAL (10^6 kkg/yr)

Use	Maximum Utilization Technically Feasible	1970 Utilization	Estimated Utilization 1971 Conditions	Potential Improved Utilization
Fly ash concrete (structural, mass and concrete products)	9-14	0.49	3.2	5.4
Lightweight aggregate	12	0.19	0.5	2.7
Raw material for cement clinker	12	0.15	0.23	---
Bricks	9	---	---	---
Filler in bituminous products	1-2	0.12	0.68	---
Base stabilizer for roads (AP[a])		0.10	0.3	> 9.1
Agriculture and land recovery (AP)	---	---	---	---
Control of mine subsidence and fires	> 1	0.01	0.68	> 0.9
Structural fill for roads construction sites, land, reclamation, etc. (AP)	---	0.29	0.5	---
Others	---	0.15	0.23	---
Total	---	1.50	6.3	---

[a] AP - annual production.

Source: 130.

TABLE 73. COMPARISON OF ASH COMPOSITION (%)

Constituent	Coal Ash	Lime Modified Ash	Dolomite Modified Ash	Lignite Ash
SiO_2	49.10	30.85	30.81	32.60
Al_2O_3	16.25	13.70	12.54	10.70
Fe_2O_3	22.31	11.59	10.72	10.0
TiO_2	1.09	0.68	0.42	0.56
CaO	4.48	33.58	17.90	18.00
MgO	1.00	1.49	14.77	7.31
Na_2O	0.05	1.12	0.72	0.87
K_2O	1.42	0.71	0.99	0.68
SO_3	0.73	2.20	8.09	2.60
C	2.21	1.12	1.76	0.11
H_2O soluble	2.51	22.11	--	8.55

TABLE 79. COMPARISON OF FBC RESIDUE COMPOSITIONS

Constituent	Ash Composition (%)[a]		
	Exxon Miniplant	Pope, Evans and Robbins Plant	Esso, England Gasifier
Fe_2O_3	9.99	15.71	0.02
CaO	13.44	4.9	10.5
MgO	0.61	0.32	0.07
SO_3	5.81	4.56	6.22
H_2O soluble	0.21	0.42	

[a] These values do not sum to 100 percent. The remainder is primarily silicon dioxide with traces of unburned carbon and metal oxides.

Source: 42.

residues collected from the bottom of the boiler. Whether these bottom residues are an ash or a slag depends on the design of the particular boiler. For any specific boiler unit, the fly ash and bottom ash will have a similar chemical composition, except that the bottom ash will be lower in carbon content.

Physically, fly ash may consist of finely divided spheroids of siliceous glass ranging from 1 to 50 microns in diameter. Some of these spheroids can be considerably finer than portland cement, and a minor fraction may consist of larger, irregularly shaped particles, some opaque and some transparent or translucent. Carbon may be present chiefly in the form of irregularly shaped particles of coke. Depending upon the type of coal and combustion conditions, the carbon content of fly ash in the United States has ranged from less than 1 to more than 20 percent. The physical and chemical characteristics of fly ash emitted from any combustion chamber depends on the type of combustion equipment and its design; the combustion or firing rate; the oxygen ratio, burning characteristics, and particle size of the coal; variations in steam load, draft, and combustion controls; and operator skill. About 70 percent of the coal ash residue may be collected as fly ash.

The bottom ash may be collected either as an ash or slag depending on the particular boiler design. The ash ranged from grey to black in color, was quite angular and had a porous surface. The slag particles normally were black, angular particles having a glass-like appearance. The bottom ash particles may be an average particle diameter size of 2.5 millimeters, and an average specific gravity of about 2.5. When there have been recovery markets for the fly ash, the fly ash has been handled dry by using a pneumatic system, storing in silos or bins on the plant site, and then transporting in closed tank trucks or rail cars. Slags to be sold were generally collected from quench tanks below the boilers to draining bins and then stored in piles until marketed. Bottom ash and slag, as granular materials, lent themselves to mechanical handling schemes.

Pulverized coal-fired units may be characterized as "wet" or "dry" bottom, with the amount of fly ash and bottom residue in each related to furnace design and the pulverization level, volatile matter, and ash content of the coal. In the wet bottom design, up to half of the total ash can be trapped within the furnace as ash or slag; however, bottom ash in "dry" bottom units amounted to only 20-25 percent of the total ash.

Coal Ash Utilization

United States

Table 80 compares ash production and utilization for the period from 1966 to 1972. By 1972, only about 16 percent of the ash and slag produced by coal combustion plants was reclaimed (11.4 percent of the fly ash, 24.3 percent of the bottom ash, and 35.3 percent of the boiler slag). Ash collection and utilization for a typical year (1971) are shown in Table 81 ; estimated 1976 ash generation is included for comparison. The main applications were as an additive to cement, a fill material for road and other construction, and a filler in asphalt mix. The "miscellaneous" use category was also quite large; Table 82 lists some of the applications aggregated under that heading. It can be inferred that a

TABLE 80 . COMPARATIVE ASH PRODUCTION AND UTILIZATION, 1966-1972

Production (kkg)	1966	1967	1968	1969	1970	1971	1972
Fly ash	15,533,855	16,701,139	17,974,729	20,234,314	24,074,886	25,175,333	28,855,791
Bottom ash	7,317,065	8,283,915	6,585,446	7,295,595	8,972,920	9,125,341	9,682,256
Boiler slag	--	--	2,317,466	2,739,954	2,541,455	4,509,421	3,430,664
Total	22,850,920	24,985,053	26,877,641	30,269,863	35,589,261	38,810,095	41,968,711

Utilization	1966	1967	1968	1969	1970	1971	1972
Total (kkg)	2,767,520	3,442,507	4,711,932	4,814,215	4,622,704	7,805,163	6,872,381
Fly ash (%)	7.9	8.2	9.6	8.13	8.13	11.7	11.4
Bottom ash (%)	21.0	25.0	25.0	25.0	18.63	16.03	24.3
Boiler slag (%)	--	--	57.8	57.8	39.06	75.21	35.3
Total (%)	12.11	13.78	17.53	15.90	13	20	16.3

Source: 88.

TABLE 81. ASH COLLECTION AND UTILIZATION, 1971

	Fly Ash (kkg)	Bottom Ash (kkg)	Boiler Slag (kkg)
Ash utilized:			
Mixed with raw material before forming cement clinker	94,550	NA[a]	83,440
Mixed with cement clinker or mixed with cement (pozzolan cement)	15,001	NA	NA
Partial replacement of cement			
Concrete products	160,725	32,094	68,551
Structural concrete	168,256	NA	NA
Dams and other massive concrete	64,784	NA	NA
Lightweight aggregate	162,294	12,648	NA
Fill material for roads, construction sites, etc.	329,663	484,156	2,384,924
Stabilizer for road bases, parking areas, etc.	33,511	7,149	44,964
Filler in asphalt mix	133,953	2,570	74,118
Miscellaneous	89,633	431,299	388,305
Total	1,252,370	969,916	3,044,302
Ash removed at plant site at no cost to utility but not covered in categories listed under "ash utilized"	1,698,938	492,514	346,346
Total ash utilized	2,951,308	1,462,430	3,390,648
Ash removed to disposal areas at company expense	22,224,448	7,663,065	1,117,941
Total ash collected	25,175,756	9,125,495	4,508,589
Estimated 1976 ash production	33,561,352	10,651,580	2,284,060

[a] Not applicable.

Source: 31.

TABLE 82. KNOWN MISCELLANEOUS USES FOR ASH AND SLAG

- Oil well cementing
- Mine fire control
- Mine subsidence control
- Neutralization of acid mine drainage
- Cleaning abrasive
- Spontaneous combustion control
- Highway bridges
- Test caps
- Refractory add mix
- Insulating cement
- Grouting
- Snow sanding
- Pipe coating
- Foundries
  - sand
  - manufacturer products
- Chemical products
- Poz-O-Pac[a]
- Sewage treatment plants (filtration)
- Substrate course (heavy construction)
- Ready mix
- Oil well drilling
- Industrial testing
- Vanadium recovery
- Ice control
- Outdoor school tracks
- Asphalt shingles
- Sandblasting grit
- Filler for glass
- Filler for fertilizer
- Filler for paint
- Filler for plastics
- Dike repair and buildings
- Drainage filter
- Aggregate
- Landfill
- Agriculture
- Dust control
- Seal coating
- Roofing granules
- Railroad base
- Mineral wool production

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[a] A pozzolan.

Sources: 1,2,4,23,26,29,31,33,34,37,40–42,46,50,53,54,59,68–70,80–82, 96, 101-103,110,111,114,116–118, 126,128–131,139,140,143–154, 167,189.

large quantity of residues was removed at no cost to utilities and found its way into useful applications. Some of these applications (and known quantities) are listed in Table 83 .

Yearly fluctuations in coal ash used suggest that the trends were influenced by market factors; thus, valid projections for future consumption were complex to make. Boiler slag has been found useful in increasing the skid resistance of road pavements. Also, a modified CMS-2 emulsified asphalt was made with bottom ash. This use increased because of the need to conserve fuel. In addition, the cost of this road paving material in areas near coal burning power plants was reduced by about one-half through use of this special type of emulsified asphalt. The use of coal ash as a raw material in the manufacture of portland cement is another application where usage has increased in the past several years. Recent research results indicated that large quantities of coal ash could also be effectively used for agriculture and land reclamation products. The use of coal ash for lightweight aggregate initially looked promising, but in the last few years this use has declined.

Effective utilization of coal ash requires that the ash satisfy the technical specifications for the application and be economically competitive. Ideally, any production or utilization process should be located close to the source of raw material; that is, near the power plant. This is not always possible; thus, transporting coal ash to where it is to be used is a major economic factor. Using trucks, fly ash was transported from a source at an average 1976 cost of \$0.04 per kkg-km (18 to 27 kkg per truck). The cost of loading and unloading was about \$2.00 per truck load. Furthermore, trucks can be expected to operate with maximum economy only in a range of about 150 to 175 miles, depending on road conditions. This would enable the trucker to get to his destination, unload, and return in the same day, avoiding any overtime or stayover.

Fly ash used in cement and concrete applications competed with natural raw materials and cement industry products. Its use was hampered by the fact that 1976 freight rates for shipping fly ash were about 20 percent higher than for the natural products because of tariffs that gave an advantage to natural or virgin materials over secondary materials.

Europe

In 1971, the Federal Republic of Germany used 79 percent of its total ash production of 6,500,000 kkg, France used 65 percent of its production of 4,185,000 kkg, and the United Kingdom used 54 percent of its production of 10,370,000 kkg.[132] About 22 percent of the total amount of ash used was employed in road construction, mainly in France and the United Kingdom. Eighteen percent of the total was used in concrete. Construction fills accounted for about 28 percent of the total used. Miscellaneous uses included coal mine fire control, addition of fly ash to foundry sand, component of blasting compounds for cleaning metal surfaces, and manufacture of acoustical block, pesticides, soaps, etc.

The wet weight of fly ash produced in Great Britain per compacted cubic meter was between 1.17 and 1.44 kkg/m^3 depending on the source and moisture content of the material. This compares favorably with the weight of traditional (British) fill material, as shown in Table 84.

TABLE 83. KNOWN USES FOR ASH REMOVED FROM PLANT AT NO COST TO UTILITY, 1971

Application	Fly Ash (kkg)	Bottom Ash (kkg)	Boiler Slag (kkg)
Manufacturing cement	46,900	NAp[a]	NAp
Mine fire control	75,250	35,325	NAp
Antiskid winter roads		161,775	150,714
Building blocks and fill material	NA[b]	13,373	NAp
Experimental soil condition	23	NAp	NAp
Miscellaneous fill material	433,567	31,534	208,105
Airport pavement	14,697	NAp	NAp
Soil stabilization	4,568	NAp	NAp
Fertilizer filler	1,198	NAp	NAp
Rubber filler	269	NAp	NAp
Vanadium recovery	181	181	NAp
Dust control	NAp	10,237	NAp
Asphaltic wear course aggregate	NAp	NAp	1,932
Total	693,916	252,425	360,751

[a] Not applicable.

[b] Not available.

Source: 31.

TABLE 84. DENSITY OF FLY ASH COMPARED WITH TRADITIONAL FILLS

Material	Compacted Density (kkg/cu m)
PFA	1.1 - 1.3
Limestone	1.6 - 2.0
Burnt colliery shale	1.7 - 2.0
Sand	≤ 2.10
Clay	≤ 1.77
Hoggin (sand/clay)	≤ 2.14
Chalk	≤ 1.75

Source: 137.

The low density ash was found to be useful for road fill, especially when embankments had to be constructed over poor soil support such as compressible alluvial clay or silt. In such situations, excessive road foundation weight could produce settlement beyond allowable limits, and may even cause complete failure of the subsoil foundations.

The stability of the fly ash is such that it has been used in Great Britain behind bridge abutments, etc. Fly ash's pozzolonic characteristics cause both a high angle of shearing resistance and high cohesion. The relatively high shear strength of fly ash together with its low density suggests its use as a support edge for selected filling behind earth retaining structures. Being both granular and porous, it has also been used as an excellent draining medium. Because of its self-hardening properties there is little settling in the compacted fly ash. Being light and fine, fly ash can be readily transported without special equipment, even in confined areas.

Fly ash has been used throughout the United Kingdom and other European countries for load-bearing structural fills at industrial sites, schools, and other locations since it exhibited excellent load-bearing and foundation strength. Furthermore, because of its low density and self-hardening capacity, fly ash made an ideal stabilized sub-foundation support for buildings built on unstable ground. In addition, fly ash has been ideal for trenching as deep trenches can be excavated using minimal trench supports. An ash fill, after hardening provided an excellent material for excavation and so it has been ideal for locating pad foundations, manholes, utilities, etc. Ash has been found to be a stable alkaline type material. Corrosion tests have demonstrated few adverse effects on cast iron, lead, copper, PVC, or ceramic pipes embedded in ash fills. It has been important, however, to remove all the soluble salts that are present by leaching new ash in order to prevent electrolytic metal corrosion or water pollution. Table 85 summarizes the hard coal and lignite ash production and utilization in Europe and the United States in 1967, 1969, and 1971. The European countries have utilized the ash residue extensively.

Specific Applications for Coal Ash

This section considers the following reported specific experience with the recovery of coal ash and limestone wet scrubber residues:

- Concrete
- Stabilized road bed construction
- Fill material
- Soil stabilization
- Neutralization of acid mine drainage
- Soil cement

TABLE 85 .DEVELOPMENT OF ASH PRODUCTION AND USE IN THE ECONOMIC COMMISSION FOR EUROPE REGION[a]

Ash Source	1967			1969			1971		
	Production (10^3 kkg)	Use		Production (10^3 kkg)	Use		Production (10^3 kkg)	Use	
		Amount (10^3 kkg)	% of Production		Amount (10^3 kkg)	% of Production		Amount (10^3 kkg)	% of Production
Hard coal									
Europe	27,250	12,477	45.3	35,710	13,630	34.8	59,922	15,983	26.7
U. S. A.	27,500	3,744	13.6	31,661	4,862	15.3	42,781	8,604	20.1
Total	54,750	16,221	29.6	67,371	18,482	27.5	102,703	24,587	23.9
Lignite									
Europe	21,370	1,380	6.4	23,017	1,278	5.5	36,353	1,658	4.6
U. S. A.	400	6	1.5	N A[b]	N A	N A	449	18	4.1
Total	21,770	1,386	6.4	23,017	1,278	5.5	36,802	1,676	4.6

[a] The UN Economic Commission for Europe (ECE) is composed of 32 countries in the European geographical region and the U.S.A. Its purpose is to present economic collaboration among all those countries.

[b] NA - Not available.

Source: 132.

- Acid soils, rectification in agriculture
- Brick manufacture
- Wastewater treatment

For this report, several experimental applications were evaluated as follows:

Concrete

The concrete can be improved by the addition of coal fly ash. Fly ash strength, resistance to sulfate attack, workability, and permeability may also help control shrinkage and evolution of heat during setting. Fly ash concrete reportedly clings less tenaciously to form and retains sharper corners and details, thus, enhancing the concrete's architectural value.

Fly ash has been valuable in cement and concrete primarily because it is a pozzolan. Pozzolans are siliceous-aluminous materials that have little or no cementitious value themselves, but, in finely divided form and in the presence of moisture, are able to react chemically with calcium hydroxide and other alkaline earth hydroxides to form compounds that harden. Fly ash in concrete can also act as a mechanical filler supplementing or replacing fine (sand) aggregate. Its spherical shape improved the workability of the plastic concrete and the ease with which it is finished.[26] In domestic sewers, concrete has been frequently exposed to attack by sulfuric acid formed through the contact of hydrogen sulfide with wet surfaces. Addition of fly ash to concrete mixes can materially increase a concrete's resistance to sulfuric acid attack.

Most fly ash concretes may need the addition of an air-entraining agent to achieve a similar air content to that obtained for regular concrete. Entraining agent requirements for a constant air content increased with the percentage of fly ash and its carbon content.

Specifications for fly ash in concrete, bituminous pavement, and light-weight aggregate should be a performance type, expressed in terms of desired characteristics for the final product. Specifications have been primarily based on experience with particular fly ashes since some fly ash may not comply with a given specification for producing an acceptable product.

The economy of using fly ash has depended almost entirely on its quality, generation, location, and cost relative to cement, although there may be economic advantages from reduced pouring and finishing time compared to standard concrete. Significant savings in using fly ash can result when large quantities of concrete are involved.

There have been some materials handling problems associated with the use of fly ash in concrete. Low viscosity, for instance, have caused difficulties in feeding and weighing. The extreme fineness of fly ash can lead to air pollution and other characteristics such as poor insulating properties of concrete used in electrical boxes and switches. Proper design of feeders and scales as well as the installation of dust-collecting systems can help reduce these difficulties.

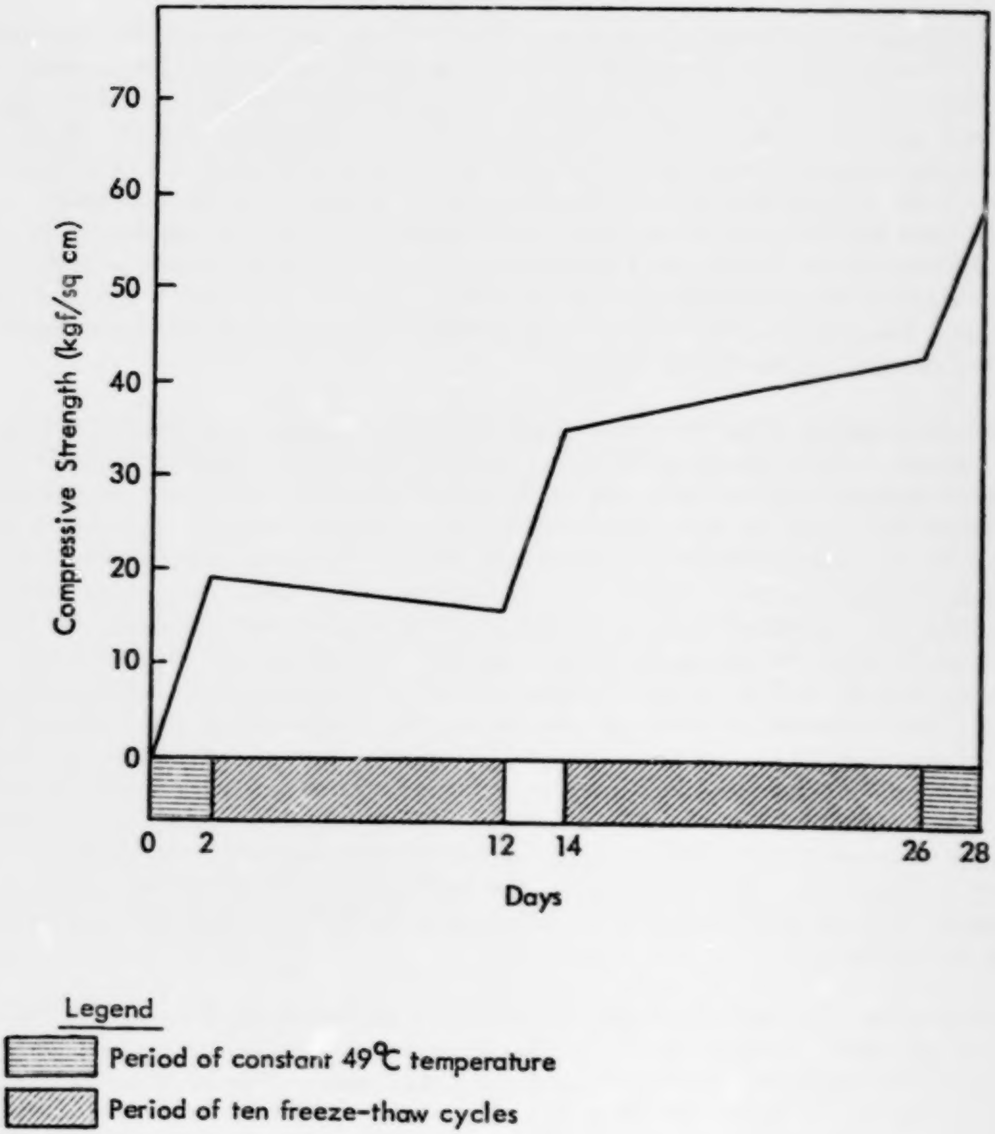
Stabilized Road Bed Construction

The use of granular materials in base and sub-base construction for road and airfield pavements has run into billions of kkg per year. Because of the vast quantities of materials needed for this type of construction, a promising market for utilizing fly ash exists. There has also been a substantial increase in the use of lime-fly ash aggregate (LFA) and lime-fly ash-cement aggregate (LCFA) mixtures in pavement construction during recent years. Many state and federal agencies have expanded their specifications to include LFA and LCFA as acceptable paving materials. Based on their properties, great potential markets can be developed for the use of LFA and LCFA materials in road construction.

LFA mixtures include blends of aggregate, lime, fly ash, and water which, when compacted to a relatively high density, produce hard surface paving materials; LCFA contains cement in addition to the other materials in LFA. Aggregates which can be successfully used in LFA and LCFA mixtures cover the entire spectrum, including sands, gravels, crushed stones, and several types of slag. Typical proportions ranged from 2 1/2 to 3 1/2 percent lime and 10 to 25 percent fly ash, depending on the gradations of the aggregates. When cement was used in the LCFA mixtures, the ratio of lime to cement was usually 3:1 to 4:1. The optimum fly ash content for a particular mix was the quantity needed to achieve maximum density in the compacted mixture, that is, it filled the voids in the aggregate lime content. The optimum mix content should be established by trial batch procedures for desired strength and durability characteristics.

Important properties of paving materials are durability, dimensional stability, strength, and stiffness. The standard test for durability of LFA and LCFA mixtures has been the cyclic freeze-thaw ASTM C593. Figure 68 shows the pattern of strength loss and gain of a typical LCFA material during alternate periods of freezing and thawing. As the curing period for the materials increased, the loss in strength decreased until ultimately the material showed a gain in strength, even during the cycle freezing and thawing period. When the latter condition existed, durability of the material was improved. All paving materials in which the aggregate particles were bound together with binders such as cement, asphalt, or lime fly-ash changed dimensions with temperature and moisture conditions. Good pavement performance required that the coefficients of linear thermal expansion of the layers be limited to less than 10^{-5}. If large dimensional changes occur, the pavement will crack excessively, permitting the infiltration of water and foreign material into the pavement with a concomitant failure in pavement performance. Dimensional changes of a typical LFA material under varying moisture and temperature conditions are shown in Figure 69. As a general rule, the coefficients of linear thermal expansion for hardened LFA and LCFA materials can be taken as 5×10^{-6}, or about the same as portland cement concrete.

The higher the compressive strength, the better the quality of the LFA mixture. The strength of LFA and LCFA was time and temperature dependent. Time and temperature versus strength relationships for typical LFA and LCFA are shown in Figures 70 and 71, respectively. The data in Table 86 shows how the strength and durability of the well-graded aggregate varied with the fly ash content.



Source: 23

Figure 68 . Effect of freeze-thaw cycles on LCFA compressive strength.

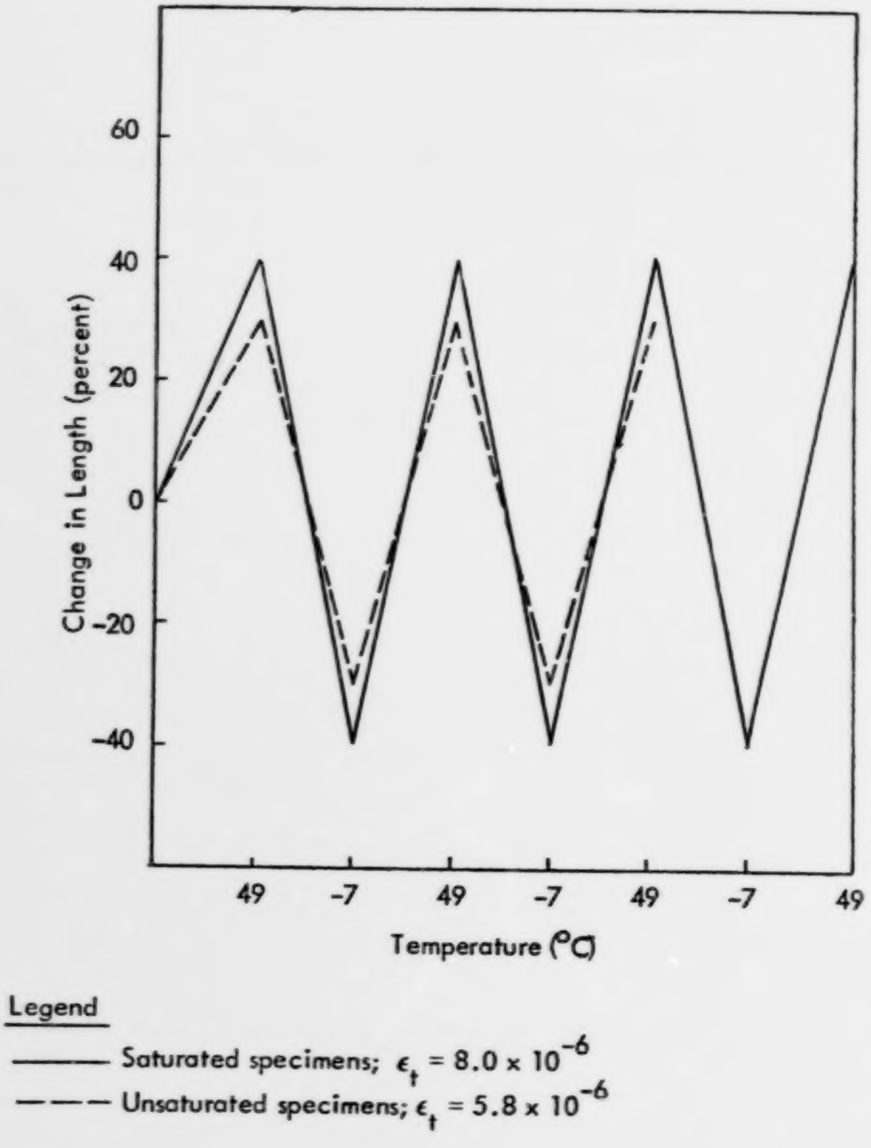


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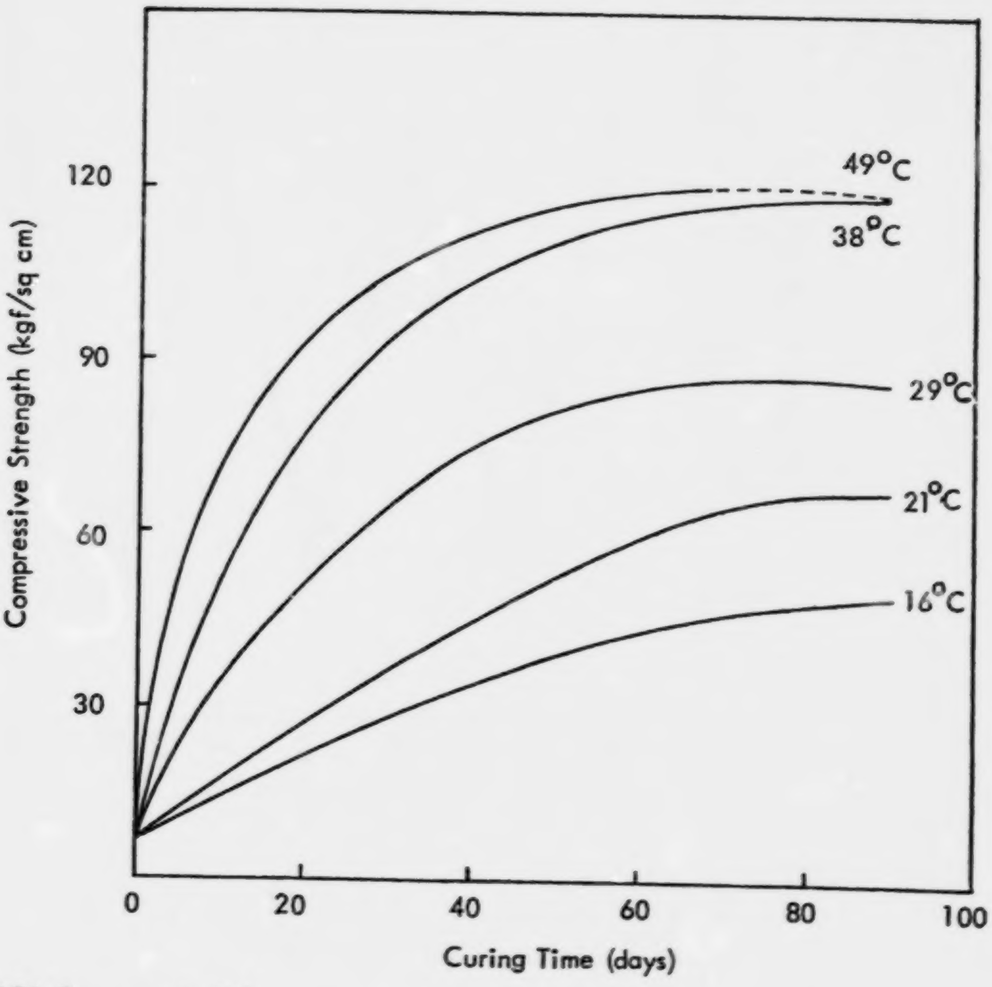
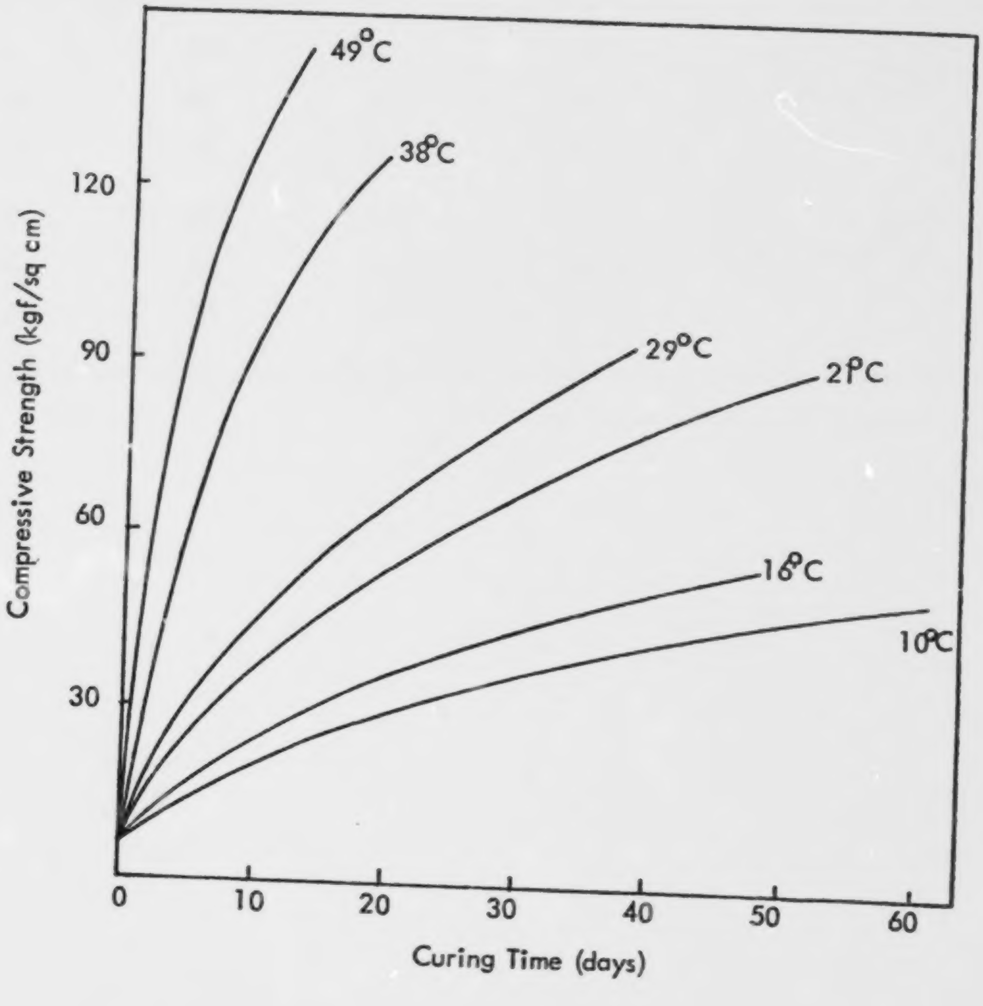
Figure 69. Change of length with temperature for cured LFA specimen.



LFA Components (%)
Lime--2.5
Fly Ash--10
Aggregate--87.5

Source: 23.

Figure 70 . Effect of curing time and temperature on LFA compressive strength.



Source: 23.

Figure 71. Effect of curing time and temperature on LCFA compressive strength.

TABLE 86. EFFECT OF FLY ASH CONTENT ON LFA STRENGTH AND DURABILITY

Aggregate Type	Fly Ash Content (%)	Compressive Strength (kgf/sq cm)	Durability	
			Weight Loss (%)	Compressive Strength (kgf/sq cm)
Crushed stone (well graded)	10	33	100	0
	12	56	23	49
	15	79	45	69
Slag (uniformly sized)	20	46	100	0
	24	54	58	3
	28	61	10	58

[a] All samples contain 3 percent lime.

Source: 23.

Figure 72 shows the effect of lime content on compressive strength of LFA mixtures; Figure 73 shows the effect on density of LFA mixtures. LCF and LCFA mixtures have an excellent performance record as paving materials. One of the best examples of the use of LFA and LCFA materials for pavement construction is at Newark, New Jersey Port Authority airport. A recent survey of the Newark airport facilities found that the primary runway and taxiway system was in excellent condition. LFA and LCFA materials have also been used extensively by the Port Authority of New York and New Jersey in the rehabilitation and upgrading of the pavements at Kennedy International Airport. Still, the application and marketing of fly ash as paving materials have not been fully exploited. The paving material market is large, and with additional effort on a national level, it appears that this market could absorb a substantial portion of the fly ash produced.

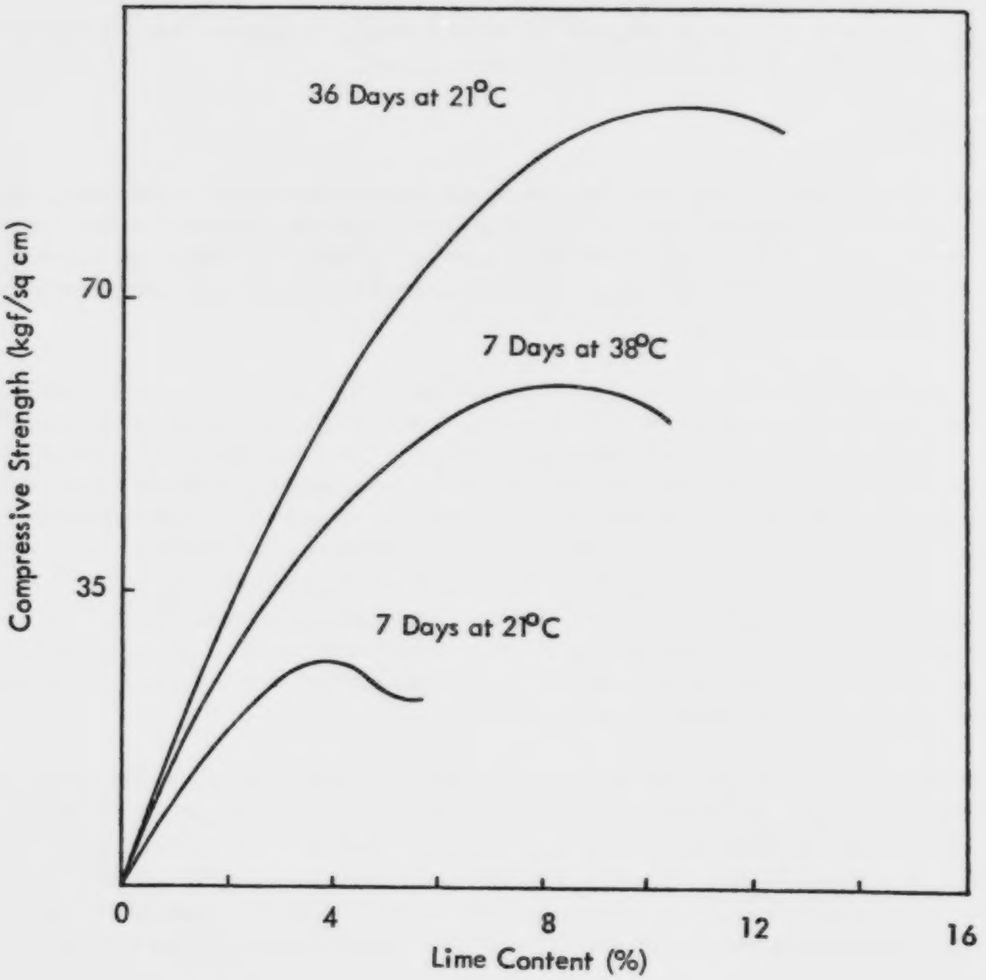
Fill Material

Most fly ash applications have required large capital investment in processing equipment, and time to develop markets. Using ash as a fill material, however, offers the advantage of minimum processing costs and a large existing market. The important material properties of fly ash as a fill material are its grain size, density, compaction characteristics, shear strength, and permeability.

The compacted dry density of fly ash ranges from 1 to 1.5 g/cu cm, which provided a dense weight when compared with most conventional fill materials; the optimum moisture content ranged from 18 to 30 percent by weight. The permeability of compacted fly ash is low, typically in the range of 10^{-3} to 10^{-5} cm per minute; however, it is satisfactory for more homogenous, compacted fill applications. Apart from slight solubility in water, the fly ash has proven to be chemically stable, with little deterioration occurring on exposure to the atmosphere. Also, since the soluble content becomes partially fixed after participation in the pozzolanic action, leachate water passing over or through the fly ash fill will pick up somewhat reduced quantities of soluble chemicals. With portland cement, the strength characteristics were enhanced by the pozzolanic action, and the fly ash/concrete mixtures showed a gradual increase of strength with time.

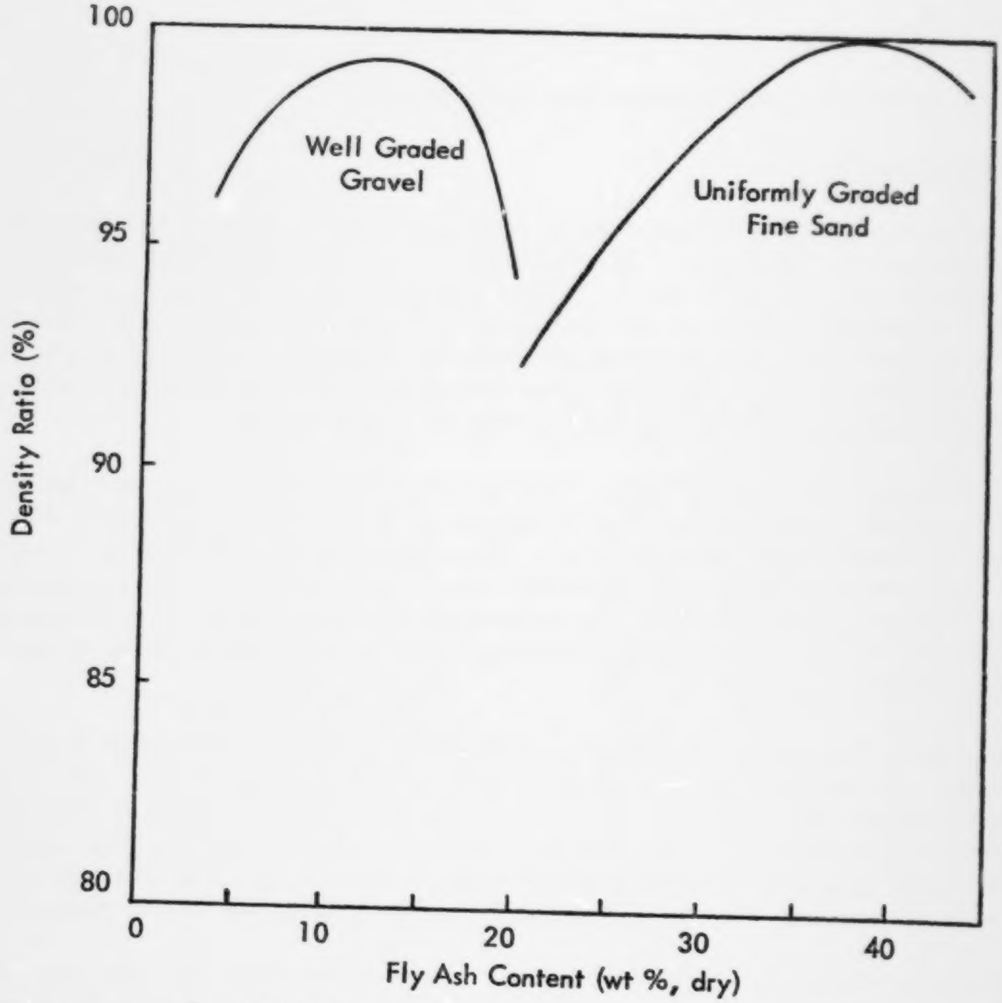
Flyash's low unit weight and low compressibility helped to reduce differential settlement between the approach embankment and the structure itself. Fly ash has also been used as structural fill to retain slurry at Grossblidgertroff Station of Houilleres du Bassin Lorraine (HBL) in eastern France. Fly ash fill dams were constructed in the valley, and the area behind them was then filled with water from a small tributory stream of the Saar River. Waste ash from the generating station was later backfilled to reclaim the land.

The major risks encountered with compacted fly-ash fills have been ash erosion (both internally and externally) and liquefaction. Internal erosion can be controlled by a properly designed drainage and filter system to ensure that fine material is not carried out of the dam as a suspension in seepage water. External erosion due to wind, rain, and wave action can be controlled by suitable cover vegetation on the downstream slope and slope protection on the upstream slope. Liquefaction is the sudden decrease in the fill shear resistance to almost zero. This is caused by collapse of the structure of the material asso-



Source: 23.

Figure 72 . Effect of lime content and curing conditions on LFA strength.



$$\text{Density ratio} = \frac{\text{Density of mixture}}{\text{Maxium density}}$$

Source: 23.

Figure 73. Effect of fly ash content on LFA density.

ciated with a sudden but temporary increase in the pore pressure. Liquefaction can be prevented by avoiding the following conditions:

- Material gradation typically in the fine sand/coarse silt range.
- Shock loadings
- Loose material with large percentage of voids
- High water table or excess pore water pressure

Soil Stabilization

The degree of stability in a soil (wet or dry) refers to its ability to resist deformation under repeated or continuing loads. Treating the soil to improve deformation resistance and strength is called stabilization.[34] A variety of stabilization methods have been available; however, no one method has been best for all soil types because each soil differs markedly in its properties and its reactions to different stabilization methods. LFA and LCFA mixtures are two materials which have been successfully used for soil stabilization in many applications, and a strong technology concerning their use has developed.

When compacted to high densities, the proper combination of lime, fly ash, aggregate and water dries into a stable, hard continuous slab which can be used as the subbase or base for bituminous or concrete paving. The amorphous glassy materials in fly ash reacted to form complex silicates and aluminate which in turn reacted with the calcium hydroxide and magnesium oxide present in lime to form a cementitious matrix. The difference between LCFA and LFA mixtures was in the addition of cement, which gives the LCFA material more strength.

Aggregate. The type of material to be stabilized is an important parameter in LFA/LCFA design. For this purpose, five categories can be identified: clays, silty soils, sandy soils, coarse granular soils, and other fill (pozzolanic materials). Treatment of clays depended greatly on the chemical composition and particle size of the material. The sodium-calcium ion balance is an important factor affecting pozzolanic strength. In practice, ratios of 5 to 9 percent lime, and 10 to 25 percent fly ash have been used in clay type soils.

Silty soils composed of less than 10 percent clay were stabilized with lime alone, or with a lime/fly ash ratio of about 1:2. Silty soils containing greater amounts of clay required larger percentages of fly ash.

Sandy soils almost always needed the addition of fly ash to promote stabilization because of their coarseness. Sandy soils containing silt and clay (10-30 percent) may be stabilized by lime alone if the clay is sufficiently pozzolanic. However, the addition of fly ash has produced better results. A lime-fly ash ratio of 1:5 has been common for sandy soils alone, but specific mixes can improve their strength and durability.

Coarse soils generally needed little (2-4 percent) or no lime to meet stability requirements for base courses. The strength of mixes containing clay or caliche can be further enhanced by the addition of fly ash (lime/fly ash ratios of 1:5 were appropriate). Materials such as scoria, cinders, chert, or water-cooled slag have been used in LFA/LCFA compositions with strengths approaching that of portland cement being reported. Fly ash not only contributed to the natural pozzolanic qualities of the above mixtures, but also improved the gradation which resulted in greater strength.

Lime. Dolomite limes (quicklime and monohydrate) resulted in 30 percent stronger products than the calcitic limes, excepth in kaolinitic material where the strengths were about the same. Currently, it is believed that the MgO in dolomitic limes acts as a catalyst in the soil-lime reaction. Calcium to magnesium ratios of 1:1 and 2:1 were optimal, and most commercial dolomitic monohydrate limes were within these limits. No optimum ratio of lime to fly ash has been found which satisfactorily stabilizes all soils. Since the lime to fly ash ratio is not very critical and lime is 5 to 10 times more costly than fly ash, it is desirable to use mixtures which maximize the percentage of fly ash.

Moisture. To maximize the strength in the hardened product, the moisture content of the LFA/LCFA mixture was at or near optimum. Optimum moisture content varied, depending on the lime/fly ash ratio. In general, the moisture content, which has resulted in the maximum bulk density of the lime-fly ash mixture, was slightly higher than that needed for the maximum hardened strength. The carbon content and fineness of the fly ash, as well as the flocculating effects of the lime, all affected the moisture content. Determining the optimum moisture content for a particular mix of lime, fly ash, and aggregate can be facilitated by preparing a diagram similar to Figure 74 . In this case, limits of 50:50 soil-lime, 50:50 soil-fly ash, and 100 percent aggregate were selected. Laboratory analysis determined that the optimum moisture concentrations for these limes were 29.2, 17.9, and 16.7, respectively. Intermediate moisture concentrations were scaled off as shown from 18 to 28 percent. The approximate optimum moisture content can then be read for any soil mix within the original limits.

Neutralization of Acid Mine Drainage

Acid mine drainage (AMD) has annually caused millions of dollars of environmental damage. Polluted water taken by downstream users for industrial, agricultural, or potable applications may have required additional pretreatment; fish and vegetation have been killed, agricultural land damaged, and an area's recreational value reduced. The problem arose when mining activities exposed pyrites and marcasites to the oxygen in the air. In the presence of moist air, sulfuric acid was formed. Every kg of iron sulfide exposed had the potential to produce as much as 1.6 kg of sulfuric acid. The extent of the pollution damage depended on how much sulfide oxidation had occurred and how much acid had been released into the environment.

There are two basic approaches to dealing with AMD: prevent its formation or prevent it from contaminating ground or suface waters. One approach which has been tried experimentally was to collect the acidic drainage as it formed and pump it to storage and treatment facilities where it was neutralized with lime or other chemicals before discharge.

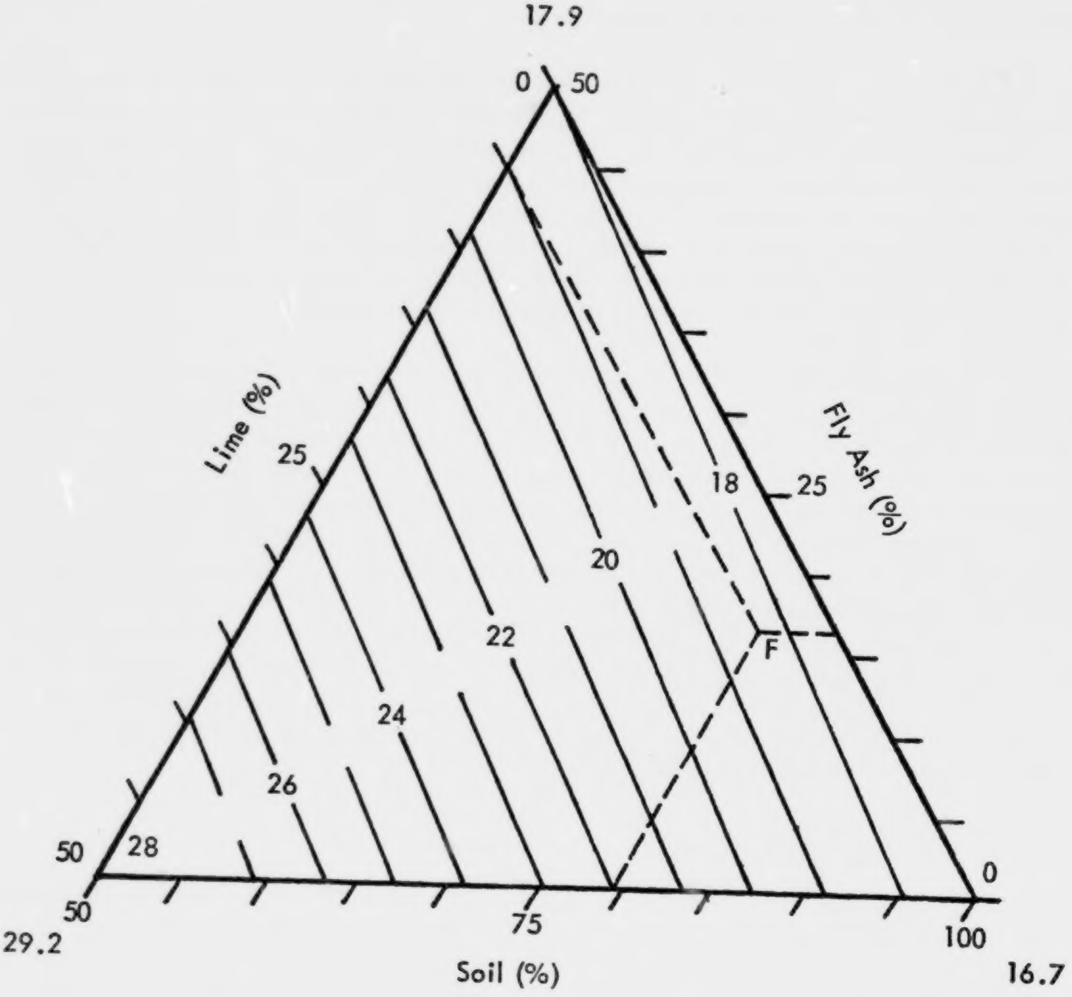


Figure 74 . LFA moisture correlation chart.

This has proven to be an expensive alternative, especially if a treatment plant is needed for every coal mine, operating or abandoned. Since the formation of acid is initiated by oxygen, attempts have also been made to prevent contact between the sulfides and air or water. Mines have been sealed to prevent water infiltration or exclude air, but results have not been successful.

Work has been done with using conventional coal fly ash residues for reclamation of surface-mine spoils.[34] The residues provided nutrients needed by the soil, served as a conditioner, and their alkalinity has also reduced the AMD.

Our preliminary analysis suggested that fluidized-bed residues could be used to neutralize AMD, both from strip and subsurface mines. Neutralization capacity varied widely with the type of residue (see Figure 75), thus potential use for AMD control will depend partially on the characteristics of the specific residues available.

The marketing potential of fluidized-bed residues for AMD is limited since coal combustion may be removed from the mining production process. Moreover, the demand for residues would depend primarily on environmental regulations, i.e. the more restrictions placed on AMD and the more stringent the requirements on strip-mine reclamation, the higher will be the future demand. Power producers must, as part of their normal production process, dispose of the residues generated. They will dispose of them by the least expensive means. The assumption of a zero f.o.b. price at the power plant for the residue would not be likely to hold for AMD application. The large quantities of residues required plus their low return to the mine owner suggest that the power plant would need to pay for some, if not all, of the freight charges.

In general, residues would most likely be used for AMD control when the mine site is as close as or closer than the landfill site. The mine could be expected to pay the cost of spreading the residues and perhaps some of the transport costs. Additionally, special environmental protection measures and other costs would likely be incurred by a landfill operator, rather than by the mine operator. It is likely, therefore, that fluidized-bed residues could be economically shipped somewhat farther for AMD neutralization than for normal landfill disposal.

Assuming the application is technically feasible and there are significant regulations concerning AMD, the market potential for fluidized-bed residues will be primarily determined by the location of mine sites relative to power plants. Residues from coal-burning plants are at this time (1978) available only for eastern United States mines, as most coal-fired power plants are now located in the East. There are several areas in the East where power plants and mining areas have been in particularly close proximity. If fluidized-bed oil gasification becomes widely adopted, many other areas will have a nearby source of residues. Coal fired combustion plants are being encouraged throughout the United States, and can be expected to become more common in most states.

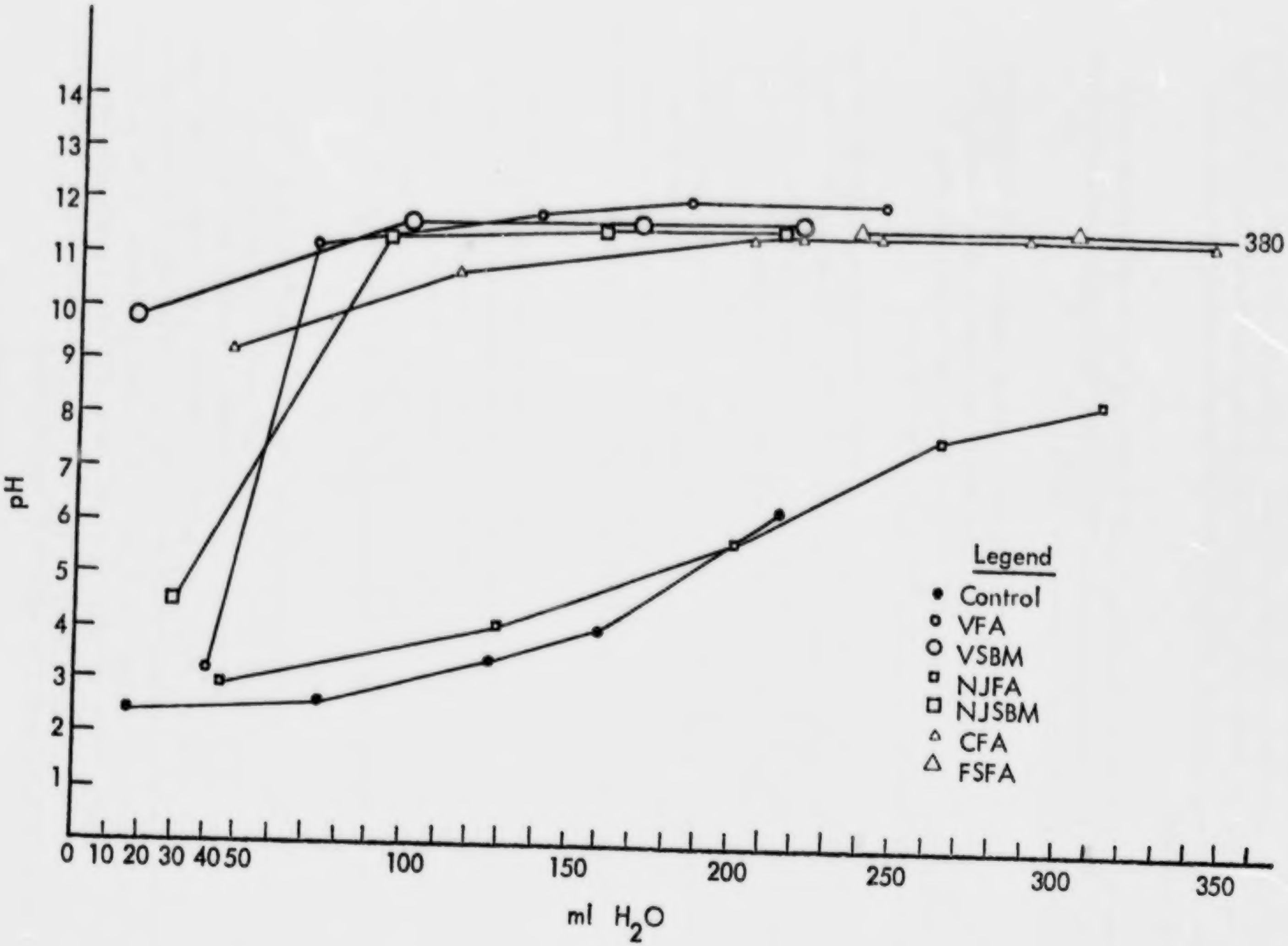


Figure 75. pH of leachate for acid mine drainage control.

Soil Cement

Soil cement is a mixture of soil, portland cement, and water. Compacted at optimum moisture content and cured to hydrate the cement, soil cement forms a strong stable base that is resistant to variations in moisture and temperature. Soil cements typically provide modules of elasticities which range from 100,000 (for clayey soils with little cement) up to 10^6 (for stronger mixtures), and have proven to be far more elastic than concrete. Soil cement mixtures have been used for base courses under pavement, roadway shoulders, patching, ditch and channel linings, and dam facings.

In general, there are three types of soil cement: compacted soil cement, cement modified soil, and plastic soil cement. Compacted soil cement contained the stoichiometric amount of cement to harden the soil,and the stoichiometric amount of water to hydrate the cement. Just enough cement and water are added to the soil to change its chemical and physical properties. Addition of cement to soil reduced the soil's plasticity and waterholding capacity, and increased its bearing value. Plastic soil cement should contain sufficient water, at the time of placing, to give the mix a consistency similar to that of plastering mortar.

The surface of a cured soil cement mixture is friable, hence it cannot be used as a running surface for motor vehicles without experiencing scuffing and pitting. It is usually overlaid with a layer of bituminous or concrete paving; the type of covering, determining to some extent, the type and thickness of the soil cement sub-base.

Soil cement has been an inexpensive paving material because of the three basic materials needed. Soil and water are either found at the site or transported only short distances. The word "soil" as used in "soil cement" means any combination of gravel, sand, silt, clay, or filler (such as cinders, shale, and chat). The water used in soil cement preparation serves two purposes: it aids in compaction by lubricating soil grains, and it is necessary for cement hydration.

Soil gradation is an important factor in proper soil cement design. Sandy and gravelly soils with about 10-35 percent silt and clay combined have been the most desirable soil cement aggregates and generally have required the least amount of cement for satisfactory curing. Coase soils containg 55 percent or more material passing through the number four sieve also make good soil cement aggregates. Sandy soils deficient in fines can make adequate soil cement, although the amount of cement needed increased as the percentage of fines decreased. Silty and clayey soils also can be used to make satisfactory soil cement; however, the higher the clay content, the greater the amount of cement needed to provide adequate hardening. Silty and clayey soils have been sensitive to weather conditions (much more so than coarse or well-graded soils).

The amount of portland cement needed to construct a suitable soil cement pavement has depended on soil type and design load. Any type of portland cement which complies with ASTM or AASHTO specifications has been satisfactory. Types 1 and 1A, normal and air-entraining portland cements are the most commonly used. Tables 87 and 88 show representative cement concentrations for various soil types.

TABLE 87. AVERAGE CEMENT REQUIREMENTS OF MISCELLANEOUS MATERIALS

Material	Percent by Volume	Percent by Weight
Caliche	8	7
Chat	8	7
Chert	9	8
Cinders	8	8
Limestone screenings	7	5
Marl	11	11
Red dog	9	8
Scoria containing plus No. 4 material	12	11
Scoria (minus No. 4 material only)	8	7
Shale or disintegrated shale	11	10
Shell soils	8	7
Slag (air-cooled)	9	7
Slag (water-cooled)	10	12

Source: 189.

TABLE 88. NORMAL RANGE OF CEMENT REQUIREMENTS FOR B AND C HORIZON SOILS[a]

AASHO Soil Group	Percent by Volume	Percent by Weight
A-1-a	5-7	3-5
A-1-b	7-9	5-8
A-2-4, A-2-5, A-2-6, A-2-7	7-10	5-9
A-3	8-12	7-11
A-4	8-12	7-12
A-5	8-12	8-13
A-6	10-14	9-15
A-7	10-14	10-16

[a] "A" horizon soils may contain organic or other material detrimental to cement reaction and may require higher cement factors. For dark grey to gret A horizon soils, increase the above cement contents four percentage points; for black A horizon soils, six percentage points.

Source: 189.

When possible, the optimum amount of moisture to add to a soil cement mixture should be determined by a laboratory test, such as AASHTO T134 "Standard Method of Test for Moisture-Density Relations of Soil-Cement Mixtures." In general, sandy mixtures will require approximately 22 l of water per sq m for a 15-cm compacted thickness. Silty and clayey mixtures will require about 32 l of water per sq m. Experienced users can, within practical limits, determine the optimum moisture content by test. Soil cement at optimum moisture contains sufficient water to form a firm cast; when squeezed in the hand, water cannot be squeezed out.

In practice, soil cement has generally been mixed in-situ or less commonly away from the construction site and then trucked in. In-place mixing has been more economical, while off-site mixing has been used only when the quantity or quality of the aggregate at the site was not adequate enough to meet the design standards. Mixing of the aggregate and cement can be either on the ground (continuous mixing) or in a mixer (either traveling or stationary). Mixers provided a better control over the amount and blending of the components. Groundmixing has been less costly and usually faster; it can be done using a dump truck or even by hand. Compaction was usually done by rollers; however, in sandy soils or coarse soils lacking in fines, compaction had to be done by vibration. Curing soil cement mixtures have had to be protected from the weather in order to prevent moisture imbalance. Bituminous coatings were generally used, but dirt, straw, and paper have all been successfully applied.

Acid soils, Rectification in Agriculture

Coal ash residues can be used to eliminate acid type agricultural soils. Soil pH is an important factor in determining the solubility of many compounds such as the concentration of heavy metals present in crops. It has been observed that in a strongly acidic soil, large amounts of metals such as iron, aluminum, and manganese may dissolve and be adsorbed on the surface of the soil particle. Plants can easily take up metals in this form.[191] Soil with a safe toxic metal content at pH 7 can easily be lethal to most crops at pH 5.5. However, it has also been found that an increase in pH has decreased the plant uptake of heavy metals. Application of sewage sludge or effluent irrigation have generally tended to lower the soil pH, and the addition of calcerous or magnesium compounds to soil have been used to correct or eliminate acidic soil conditions.

Related information of the effects of zinc level and soil pH on chard plants are shown in Table 89 . Inorganic zinc (and cadmium at one percent of the added zinc) was added to a sassafras sandy loam soil and the pH was adjusted to 5.3, 6.4, or 7.2 in the metal amended soil. The concentration of zinc uptake in plants was significantly reduced when the soil pH was increased by the addition of lime.

Addition of sulfur has been shown to reduce the soil pH. The reduction of soil pH was directly proportional to the quantity of sulfur added. Lowering the soil pH increased the concentration of metals as well as certain other elements such as silicon, phosphorus and potassium, as shown in Table 90 .

The Virginia Polytechnical Institute, in another field test using fly ash as a fertilizer, was

TABLE 89. EFFECTS OF ADDING Zn AND VARYING THE pH IN THE SOIL ON Zn CONTENT AND YIELD REDUCTION OF CHARD LEAVES

Added Zn ppm	Soil pH[b] 5.3	6.4	7.2
1.31	210	116	12
32.7	754	237	74
65.4	1058(7)[a]	337(5)	100
131.0	2763(41)	765(9)	177
262.0	2692(95)	1678(22)	406(27)

[a] Yield reduction in parentheses (%).
[b] g. Zn/g dry weight.

Source: 191.

TABLE 90. EFFECTS OF SOIL pH ON SOYBEAN PLANT'S MINERAL UPTAKE

Elements in ppm	Soil pH 7.4[a]	6.1[b]	% Increase	Elements yield 7.4[a]	g l plant[c] 6.2[b]
Fe	31	81	261.2	5.6	18.5
Mn	47	209	444.6	8.5	47.7
Zn	40	68	170.0	1.72	2.87
Co	6.6	12.3	186.3		
Mo	9.5	12.6	132.6		
Al	9.6	16.4	170.8		
B	72	123.0	170.8		
Ni	4.4	7.7	175.0		
Si	2000	3800	190.0		
P	4300	6500	151.1		
K	17,300	25,900	149.7		

[a] No sulfur added.
[b] 10% sulfur added.
[c] P154619-5-1 soybean variety.

Source: 192.

seeking to determine (1) the plant nutrients available in fly ash, and (2) the effects of different fly ash application rates. Research on revegetating several barren experimental sites has proven that fly ash could act as a neutralizing agent, diluent, and soil conditioner to provide needed nutrients which enhance vegetation growth.[84]

The United States Park Service, Washington, D.C., has been testing sintered fly ash for use as an additive to soils subjected to continuous use (bicycle paths, camping areas, hiking trails, picnic areas). In this application, sintered fly ash would be added because of its porosity and resistance to degradation.

Brick Manufacture

Using fly ash as an additive can extend the life of a clay or shale deposit; this is of particular value to brick plants with limited raw materials supplies. Extensive research on fly ash in brick has been done at the Coal Research Bureau of West Virginia University. This research has yielded information on the tolerance levels for many fly ash constituents which when exceeded, contributed to a poor quality brick. These constituents included: water soluble minerals, water soluble sulfur, carbon, iron, and the alkaline earths. The first commercial fly ash brick plant using the process developed at the Coal Research Bureau has been operating in Edmonton, Alberta. The plant has a design capacity of 35 million bricks per year. Economic studies currently under way indicated that the cost of the Coal Research Bureau process was less than that of the conventional clay-brick manufacturing process. At the time of this report, several firms were currently examining the process for commercial exploitation. Research was under way on coloring and texturing the brick, and on producing large size bricks.

Water Treatment

Fly ash as a treatment material for reclaiming small eutrophic or algae-overgrown lakes was being investigated at Notre Dame University. It has been shown that fly ash can remove phosphates in the water and seal the bottom mud so that the release of pollutants can be controlled. A process for the removing of phosphates from water by using fly ash has been developed at the Polytechnic Institute, Brooklyn, New York. When used for water treatment, fly ash can (1) increase the growth of flocs and thus enhance settling, (2) condition the waste sludge as a physical aid to filtration, (3) remove phosphates, and (4) absorb organic molecules in solution.

Miscellaneous

Industrial applications for the hollow, spherical, and extremely light-weight fly ash particles known as cenospheres were being developed at Washington State University. One application, known as "syntactic foam," was used to achieve buoyancy in deep ocean environments. Syntactic foam was formed by vacuum impregnating cenospheres with an appropriate resin. Research on aerospace applications of cenospheres has been under way at the Grumman Aerospace Corporation. From this research, a closed pore insulation material for use on the space shuttle has been developed. A unique application using cenospheres in the production of tape for fire-proofing and insulating high-voltage electrical cable has been developed by the Quelcor Corporation.

Specific Applications of Lime/Limestone Wet Scrubber Residues

"Modified fly ash," the solid by-product from lime/limestone wet-scrubbing, is a new solid waste material which has different chemical and physical properties from regular fly ash. Modified fly ash has had little potential for mineral separation and benefication and, therefore, must be used in its homogeneous state. The Coal Research Bureau has developed several promising uses for modified fly ash. Several potential applications which have been considered are:

- Soil amendment
- Highway construction
- Aerated concrete
- Poured concrete

Soil Amendments

Dried modified fly ash can be used as a soil amendment to increase the calcareous component and to neutralize acidic soil. Modified fly ash may also increase the concentrations of boron and other trace elements, and also increase the texture and drainage characteristics of soils. Further research is needed to determine if pollution would be created by water leaching.

Highway Construction

Combustion Engineering participated in a project with the Research and Development Division of the Federal Highway Department to study the use of residues as a highway construction material. The program was part of the International Transportation Exposition (Transpo '72) that was held from May 24 to June 4, 1972 at the Dulles Airport in Washington, D.C. To accommodate the 50,000 automobiles and 600 buses arriving daily at the exposition, a 49-hectare parking lot was constructed. The Research and Development Division of the Federal Highway Administration used this opportunity to demonstrate the recycling of waste products as highway construction materials. The major portion of the parking lot was paved with a mixture of modified fly ash and sulfate sludge from an acid plant.

Aerated Concrete

Aerated concrete has been widely developed in Europe. Almost all new factory buildings is Sweden and West Germany have been constructed, in part, using this material. Aerated concrete is a light-weight structural material consisting of small non-communicating gas cells entrained in a calcium silicate matrix. A process flow sheet for the production of aerated or foamed cellular concrete from modified ash is shown in Figure 76. It was necessary to add cement and a gas-producing agent to the modified fly ash in making this product. After the concrete was poured into the mold, the form was autoclaved for 16 hours. Commercial aerated material can be sawed, nailed, drilled, screwed, or glued like wood, but has the thermal and fire resistant properties of concrete. Potential uses include nonload-bearing walls, sandwich construction with brick or concrete for insulating purposes, and interior surfacing for exterior walls. It can be formed in any desired shape or cut from panels and is suitable for modular construction.

Poured Concrete

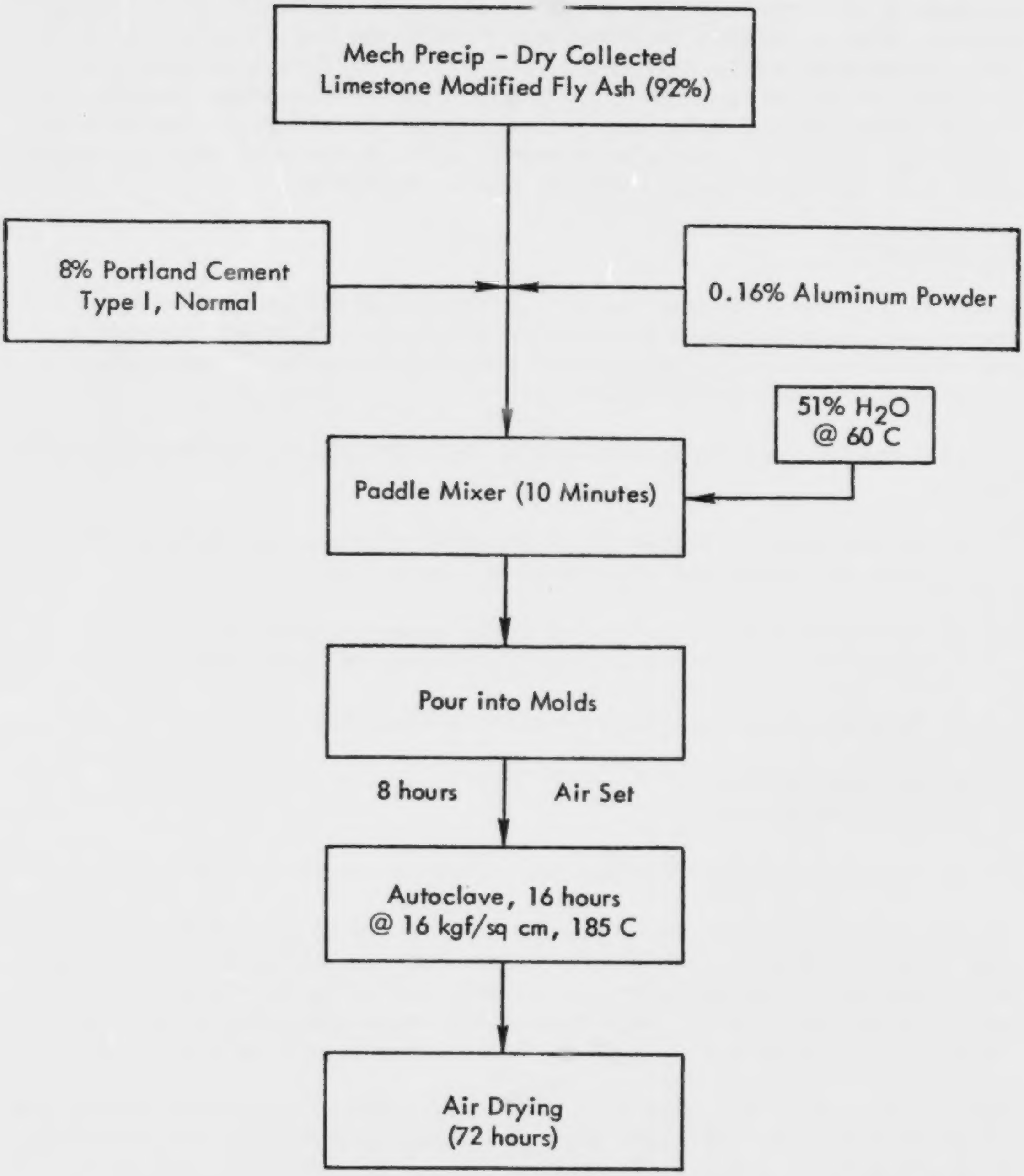
Figure 77 is a process flow sheet for the manufacture of poured concrete materials. The material was poured into molds for curing and autoclaved for 16 hours. The resulting poured concrete block had a density of 1.5 g/cu cm. The residue did not require grinding or curing prior to use in poured concrete.

The advantages of producing autoclaved calcium-silicate products from limestone fly ash include:

- No SO_2 capture or marketing problems would result since processing would occur below the temperature for sulfur dioxide regeneration.
- Little or no storage or curing time would be required before use since structural materials produced have been shown to be durable, pre-shrunk, and pre-strengthened.
- No exotic equipment would be required for production.
- Minimum pollution would occur at the plant since all rejects and process waters may be recycled.
- A potentially large market may exist in low-cost housing or other construction.

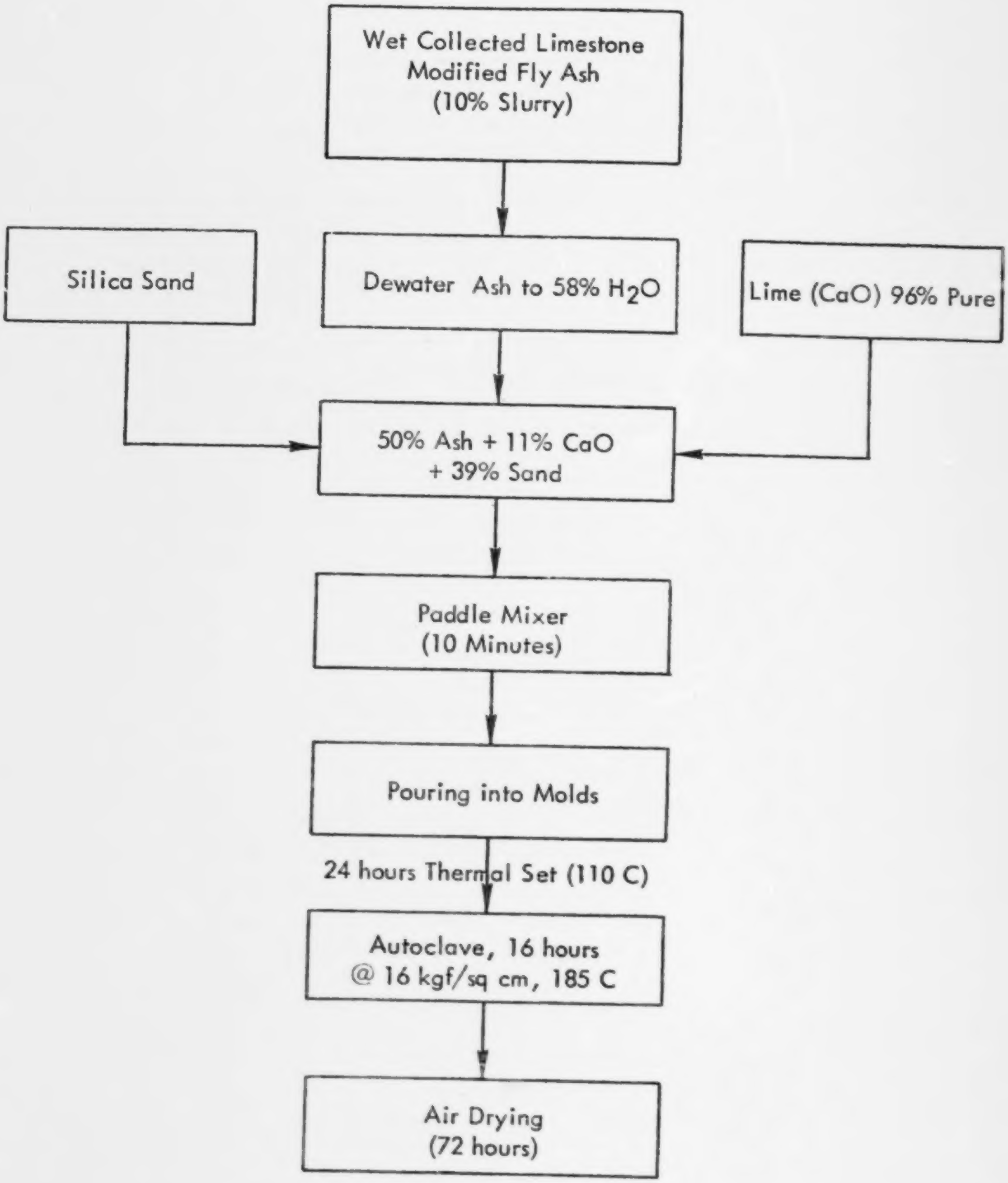
Because absorbed sulfur dioxide is liberated when modified fly ash is heated, it was necessary to find a technique for totally using the ash which would either lock the sulfur into the final product or not require heating. Autoclaving has had the advantage of locking sulfur into the final product. The products with the greatest potential for using modified fly ash are: bricks and blocks, aerated or foamed concrete, and concrete materials.

Calcium silicate (CS) brick production has been examined as a potentially large tonnage application of limestone modified fly ash. Bricks produced by this method have the advantage of binding the sulfur components within a calcium-silicate matrix, and have surpassed the standards for conventional sand-lime brick. Figure 78 is a process flow sheet for the production of CS brick. Mixing and humidity curing have been two important process parameters in producing CS brick. Promising areas for using calcium silicate brick include low-cost construction materials, interior walls, decorative walls, patios, and thermal or acoustic insulation.


Mech Precip - Dry Collected
Limestone Modified Fly Ash (92%)
8% Portland Cement
Type I, Normal
0.16% Aluminum Powder
51% H2O
@ 60 C
Paddle Mixer (10 Minutes)
Pour into Molds
8 hours
Air Set
Autoclave, 16 hours
@ 16 kgf/sq cm, 185 C
Air Drying
(72 hours)

Source: 46.

Figure 76 . Aerated or foamed cellular concrete production flow diagram.


Wet Collected Limestone
Modified Fly Ash
(10% Slurry)
Silica Sand
Dewater Ash to 58% H2O
Lime (CaO) 96% Pure
50% Ash + 11% CaO
+ 39% Sand
Paddle Mixer
(10 Minutes)
Pouring into Molds
24 hours Thermal Set (110 C)
Autoclave, 16 hours
@ 16 kgf/sq cm, 185 C
Air Drying
(72 hours)

Source: 46.

Figure 77. Formed concrete production flow sheet.

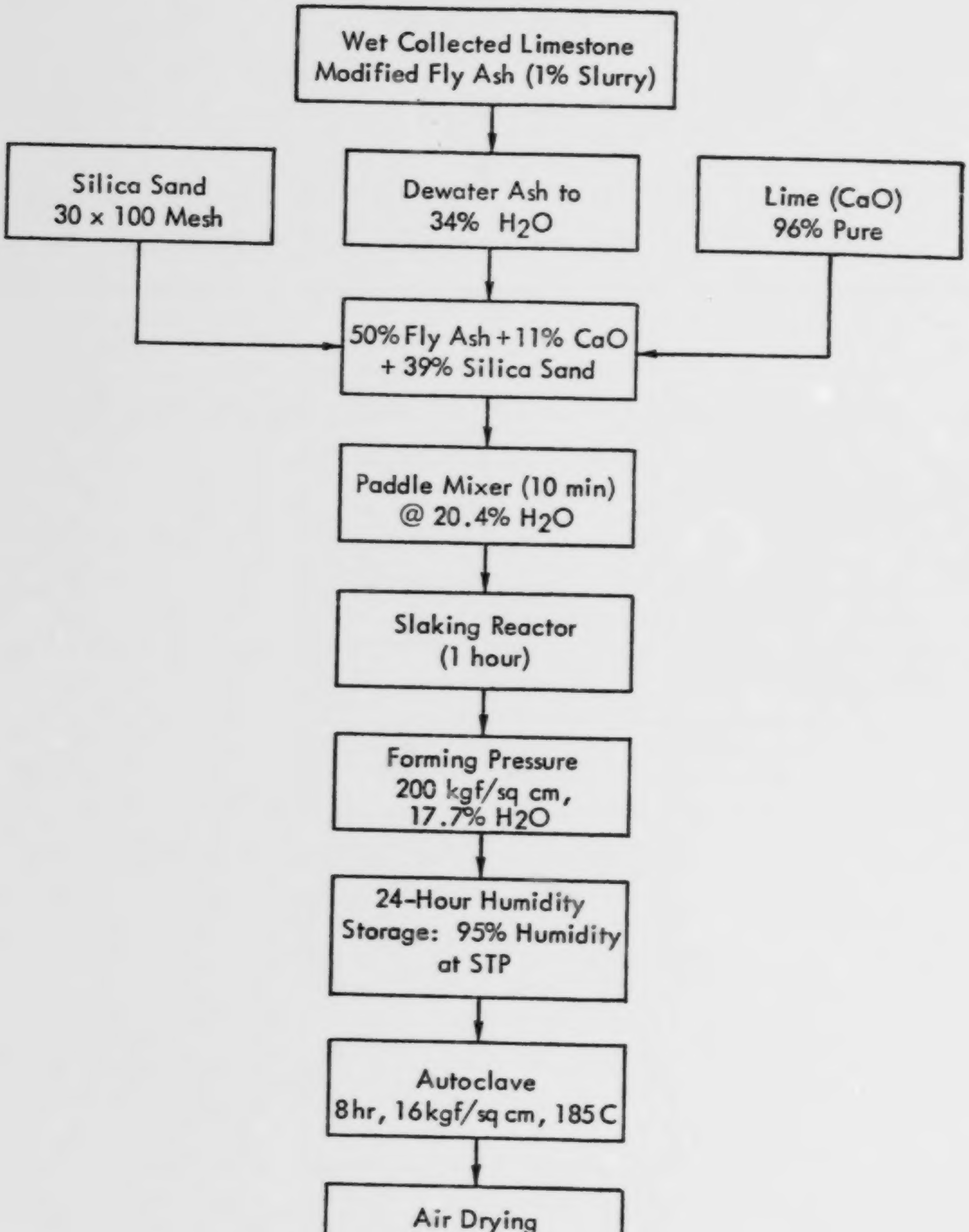

Wet Collected Limestone Modified Fly Ash (1% Slurry)
Silica Sand 30 x 100 Mesh
Dewater Ash to 34% H_2O
Lime (CaO) 96% Pure
50% Fly Ash + 11% CaO + 39% Silica Sand
Paddle Mixer (10 min) @ 20.4% H_2O
Slaking Reactor (1 hour)
Forming Pressure 200 kgf/sq cm, 17.7% H_2O
24-Hour Humidity Storage: 95% Humidity at STP
Autoclave 8hr, 16kgf/sq cm, 185 C
Air Drying (72 hours)

Figure 78. CS brick production flow diagram.

Potential Structural Materials Applications of Fluidized-Bed Residues

Several beneficial materials applications for conventional coal-combustion residues were discussed earlier in this chapter. Because of limited material, it was not possible to undertake a comprehensive structural testing program investigating all the possible uses of fluidized-bed coal combustion residues; several preliminary screening tests were run on applications for the residues in concrete and asphalt. These tests are listed in Table 91 . Concrete and asphalt are discussed separately below.

Concrete

Procedure. The residue addition to concrete was tested for compressive strength. Twenty batches of concrete were mixed, differing in the amount and type of residue added. Two of the twenty were control samples in which no residues were added. Four sample specimen cylinders were made from each batch. The procedure followed for making the cylinders was ASTM C192-69 ("Standard Method of Making and Curing Concrete Test Specimens in the Laboratory"); the cylinders were approximately 5 cm in diameter by 10 cm in length. Table 92 gives the composition of each batch. The mixtures are considered "rich mixes" because of the high cement content (approximately 15 percent).

One sample from each batch was tested after curing for seven days; another after twenty-eight days. After curing, the cylindrical molds were removed and the diameters of the cylinders were measured to obtain average cross-sectional area; the results are shown in Tables 93 and 94 . Each cylinder was then capped to prepare them for the actual compressive strength tests. The results of the tests are presented in Table 95 for the seven day curing and in Table 96 for the twenty-eight day curing.

Results. The results are shown graphically in Figures 79 to 82 , which plot compressive strength versus residue strength. In general, the strength increased with curing time for all the fluidized-bed residues. The only exception was the concrete containing more than about 18 percent by weight of EFA. This was due to the unique property of the 7-day cured EFA. Like the other residues, the strength of the concrete decreased from 5 to 15 percent residue; however, at 25 percent residue content, the compressive strength had increased to a value higher than the concrete containing 5 percent residue.

Optimum residue percentages varied widely. Strengths increased with increasing residue concentration for fly ash (7-day cure) and spent bed materials from the Exxon, New Jersey, pressurized miniplant. On the contrary, with the exception of VFA (28-day cure) and the EFA (7-day cure), strengths decreased with increasing content of residues from the PER, Virginia atmospheric pressure unit and from the Esso gasifier. The following concrete test specimens showed unconfined compressive strengths greater than the control specimens: 5 percent VSBM/7-day cure; 5,15, and 25 percent VSBM/28-day cure; 5,15, and 25 percent NJFA/28-day cure; and 5 percent VFA/28-day cure. The 25-percent NJFA/7 day cure material was nearly equal to the control.

TABLE 91 . POTENTIAL STRUCTURAL MATERIALS APPLICATIONS: TESTS PERFORMED

Application	Test Description	Method[a]
Concrete	Compressive strength of cylindrical concrete specimens	ASTM C39
Asphalt	Compressive strength of bituminous mixtures	ASTM D1074
	Effect of water on cohesion of compacted mixtures	ASTM D1075
Pozzolan cements		
LFA mixtures	Compressive strength of cylindrical concrete specimens	ASTM C-593
Soil cement	Compressive strength of molded soil-cement	ASTM D1633
Load-bearing fill	Classification for engineering purposes	--
	Direct shear: soil under consolidated condition	ASTM D3080

[a] Reference numbers as found in 1974 Annual Book of ASTM Standards. Philadelphia: American Society for Testing and Materials (ASTM), 1974.

TABLE 92. COMPOSITION OF CONCRETE TEST CYLINDERS

Batch No.[a]	Type of Residue[b]	Concrete Composition (% by weight) Residue	Fine Aggregate	Portland Cement	Water
1	Control	0	71.5	15.2	13.3
2	VSBM	5.2	64.8	14.9	15.1
3		15.8	53.6	14.7	15.9
4		25.0	41.0	14.0	20.0
5	NJFA	5.3	64.7	14.9	15.1
6		15.7	53.4	14.7	16.2
7		25.0	41.0	14.0	20.0
8	VFA	5.2	63.7	14.6	16.5
9		15.0	51.0	14.0	20.0
10		24.7	40.5	13.8	20.9
11	Control	0	71.5	15.2	13.3
12	NJSBM	5.3	64.7	14.9	15.1
13		15.2	53.7	14.7	16.4
14		25.7	43.2	14.7	16.4
15	EFA	5.2	64.8	14.9	15.1
16		15.2	53.7	14.7	16.4
17		25.1	41.0	14.0	20.0
18	ESBM	5.3	64.7	14.9	15.1
19		15.2	53.7	14.7	16.4
20		25.1	41.0	14.0	20.0

[a] Two samples for each batch.

[b] Residue source code presented in Table 6.

TABLE 93 . DIAMETER AND AREA OF CONCRETE TEST CYLINDERS: SEVEN-DAY CURE

Batch No.[a]	Diameter (cm)				Average Diameter (cm)	Average Cross-sectional Area (sq cm)
	b	b	c	c		
1	5.37	5.77	5.69	5.45	5.57	24.37
2	5.45	5.77	5.85	5.45	5.63	24.89
3	5.61	5.77	5.69	5.69	5.69	25.43
4	5.77	5.77	5.37	5.77	5.67	25.25
5	5.45	5.77	5.77	5.61	5.65	25.07
6	5.37	5.85	5.85	5.37	5.61	24.72
7	5.53	5.69	5.69	5.61	5.63	24.89
8	5.77	5.45	5.45	5.69	5.59	24.54
9	5.77	5.45	5.45	5.77	5.61	24.72
10	5.61	5.53	5.53	5.61	5.57	24.37
11	5.40	5.32	5.40	5.32	5.36	22.56
12	5.24	5.24	5.40	5.40	5.32	22.23
13	5.40	5.40	5.24	5.24	5.32	22.23
14	5.40	5.40	5.24	5.24	5.32	22.23
15	5.40	5.40	5.24	5.24	5.32	22.23
16	5.40	5.40	5.32	5.24	5.34	22.40
17	5.40	5.40	5.16	5.24	5.30	22.06
18	5.32	5.32	5.24	5.24	5.28	21.90
19	5.40	5.40	5.32	5.32	5.36	22.56
20	5.40	5.40	5.32	5.32	5.36	22.56

[a] Two samples for each batch.

[b] First sample of the batch; two diameter measurements taken to minimize effect of random irregularities.

[c] Second sample of the batch; two diameter measurements taken to minimize effect of random irregularities.

TABLE 94. DIAMETER AND AREA OF CONCRETE TEST CYLINDERS: TWENTY-EIGHT DAY CURE

Batch No.[a]	Diameter (cm)				Average Diameter (cm)	Average Cross-sectional Area (sq cm)
	[b]	[b]	[c]	[c]		
1	5.29	5.29	5.45	5.45	5.37	22.65
2	5.45	5.45	5.21	5.21	5.33	22.31
3	5.37	5.37	5.45	5.37	5.39	22.82
4	5.37	5.37	5.37	5.37	5.37	22.65
5	5.29	5.29	5.45	5.45	5.37	22.65
6	5.45	5.45	5.29	5.37	5.39	22.82
7	5.29	5.29	5.45	5.45	5.37	22.65
8	5.29	5.29	5.45	5.37	5.35	22.48
9	5.45	5.45	5.29	5.29	5.37	22.65
10	5.45	5.37	5.37	5.37	5.39	22.82
11	5.32	5.32	5.40	5.40	5.36	22.56
12	5.40	5.40	5.24	5.24	5.32	22.23
13	5.32	5.32	5.32	5.32	5.32	22.23
14	5.40	5.40	5.24	5.24	5.32	22.23
15	5.40	5.40	5.24	5.24	5.32	22.23
16	5.40	5.40	5.24	5.16	5.30	22.06
17	5.40	5.40	5.24	5.32	5.34	22.40
18	5.40	5.40	5.16	5.24	5.30	22.06
19	5.40	5.40	5.24	5.24	5.32	22.23
20	5.40	5.40	5.24	5.24	5.32	22.23

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[a] Two samples for each batch.

[b] First sample of the batch; two diameter measurements taken to minimize effect of random irregularities.

[c] Second sample of the batch; two diameter measurements taken to minimize effect of random irregularities.

TABLE 95. RESULTS OF COMPRESSIVE CONCRETE STRENGTH TEST AFTER SEVEN DAYS

Batch No.	Type of Residue[a]	Residue Content (%)	Cross-Sectional Area (sq cm)	Max Load Before Failure (kg)	Time Load Applied (sec)	Strength (kg/sq cm)	Fracture Description
1	Control	0	24.37	3,856	2.0	158.2	Conical, diagonal
2	VSBM	5.2	24.89	4,763	1.8	191.4	Vertical and less diagonal
3		15.8	25.43	3,175	1.6	124.9	Conical, diagonal
4		25.0	25.25	2,948	1.8	116.8	Diagonal
5	NJFA	5.3	25.07	3,402	1.8	135.7	Conical, diagonal
6		15.7	24.72	3,629	1.5	146.8	Vertical, diagonal
7		25.0	24.89	3,856	1.5	154.9	Diagonal
8	VFA	5.2	24.54	2,948	1.6	120.1	Conical with small vertical
9		15.0	24.72	2,495	1.5	100.9	Diagonal
10		24.7	24.37	2,268	1.4	93.1	Diagonal
11	Control	0	22.56	3,855	20	170.88	Conical, diagonal
12	NJSBM	5.3	22.23	2,041	20	91.81	Diagonal, vertical conical
13		15.2	22.23	2,494	10	112.40	Diagonal, vertical
14		25.7	22.23	2,721	10	122.40	Diagonal, vertical, shearing
15	EFA	5.2	22.23	3,175	10	142.83	Diagonal, vertical
16		15.2	22.40	1,814	10	80.98	Diagonal, vertical
17		25.1	22.06	3,401	17	154.17	Diagonal, vertical
18	ESBM	5.3	21.90	1,587	7	72.47	Diagonal, vertical
19		15.2	22.56	1,361	10	60.33	Diagonal
20		25.1	22.56	1,134	10	50.27	Diagonal, vertical

[a] Residue source code presented in Table 6.

TABLE 96. RESULTS OF COMPRESSIVE CONCRETE STRENGTH TEST AFTER TWENTY-EIGHT DAYS

Batch No.	Type of Residue[a]	Residue Content (%)	Cross-Sectional Area (sq cm)	Max Load (kg)	Time Load Applied (sec)	Strength (kg/sq cm)	Fracture Description
1	Control	0	22.65	3,629	3.0	160.2	Conical and diagonal
2	VSBM	5.2	22.31	4,763	2.5	213.5	Conical and diagonal
3		15.8	22.82	4,536	2.5	198.8	Conical and diagonal
4		25.0	22.65	3,856	2.5	170.2	Conical and diagonal
5	NJFA	5.3	22.65	5,443	3.5	240.3	Conical and diagonal
6		15.7	22.82	5,670	3.0	248.5	Conical and diagonal
7		25.0	22.65	5,897	3.0	260.4	Conical and diagonal
8	VFA	5.2	22.48	4,536	4.0	201.8	Conical and diagonal
9		15.0	22.65	2,948	2.0	130.2	Conical and diagonal
10		24.7	22.82	2,722	3.0	119.3	Conical and diagonal
11	Control	0	22.56	5,443	8.0	241.0	Conical and diagonal
12	NJSBM	5.3	22.23	2,722	10.0	122.4	Conical and diagonal
13		15.2	22.23	3,175	6.0	142.8	Conical and diagonal
14		25.7	22.23	3,856	8.0	173.5	Conical and diagonal
15	EFA	5.2	22.23	3,629	7.0	163.2	Conical and diagonal
16		15.2	22.06	2,495	5.0	113.1	Conical and diagonal
17		25.1	22.40	1,361	3.0	60.8	Conical and diagonal
18	ESBM	5.3	22.06	3,629	6.0	164.5	Conical and diagonal
19		15.2	22.23	1,814	5.0	81.6	Conical and diagonal
20		25.1	22.23	1,134	5.0	51.0	Conical and diagonal

[a] Residue source code presented in Table 6.

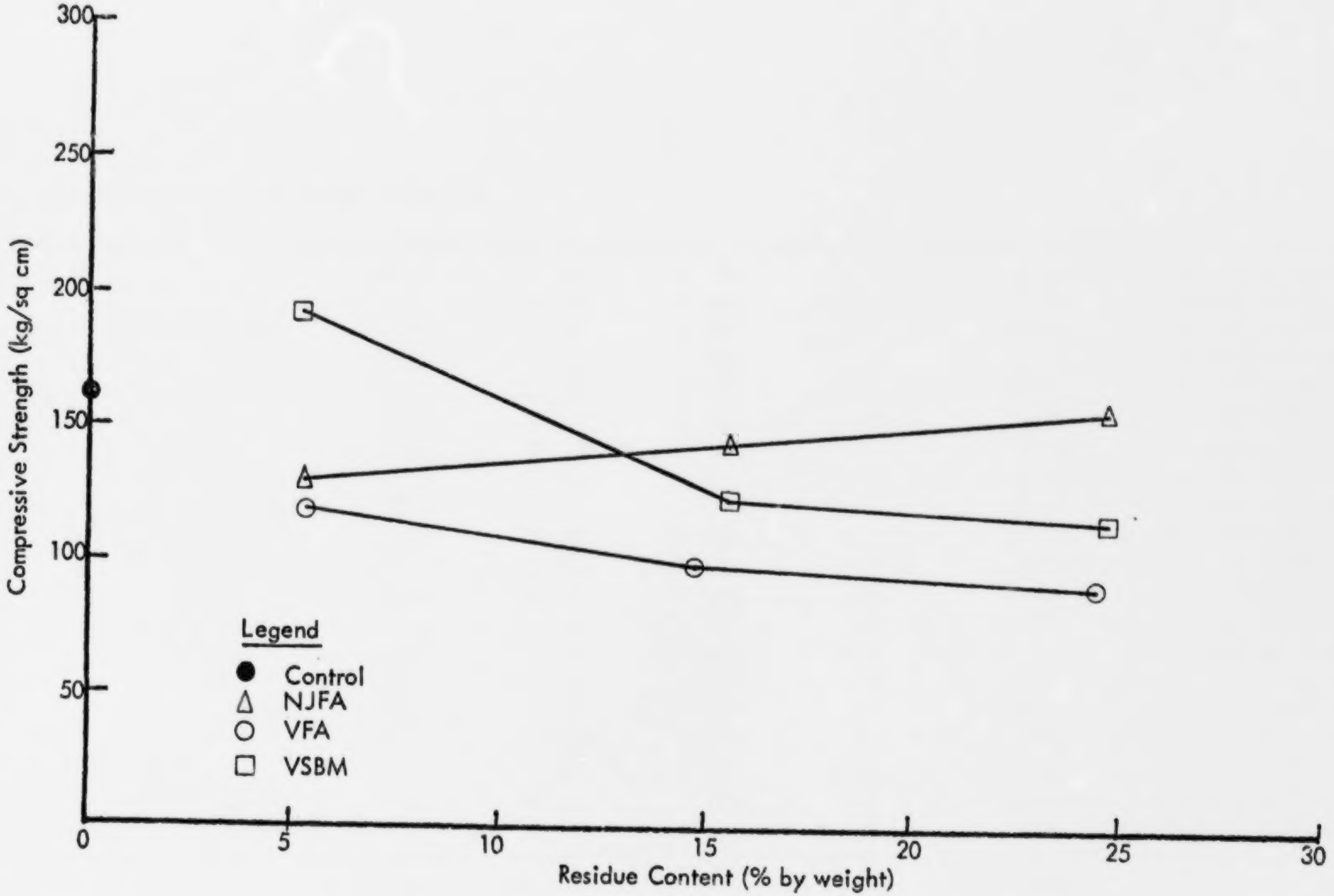

Figure 79. Concrete, compressive strength tests: NJFA, VFA, VSBM after seven day cure.

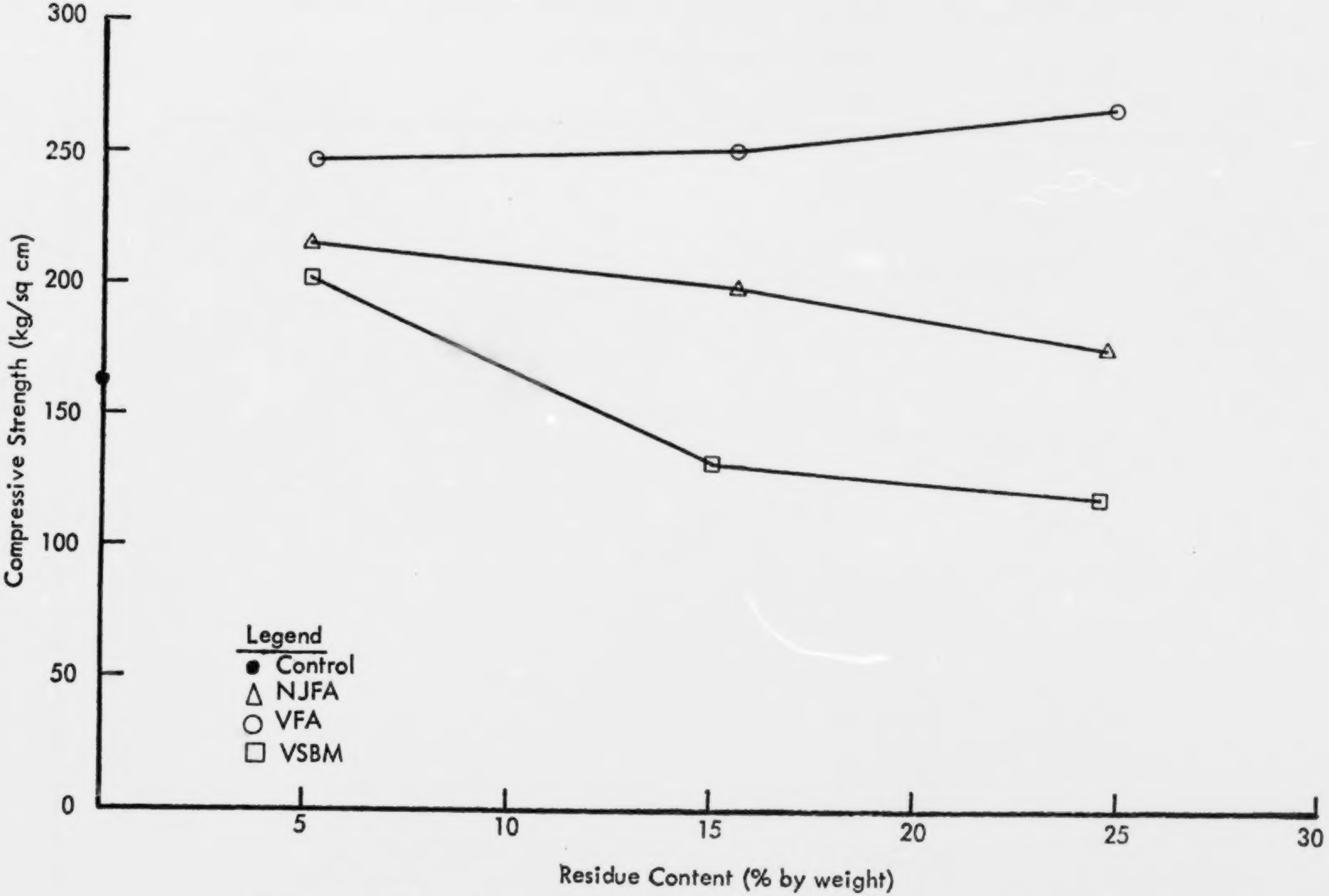

Figure 80 . Concrete compressive strength tests: NJFA, VFA, VSBM after 28-day cure.

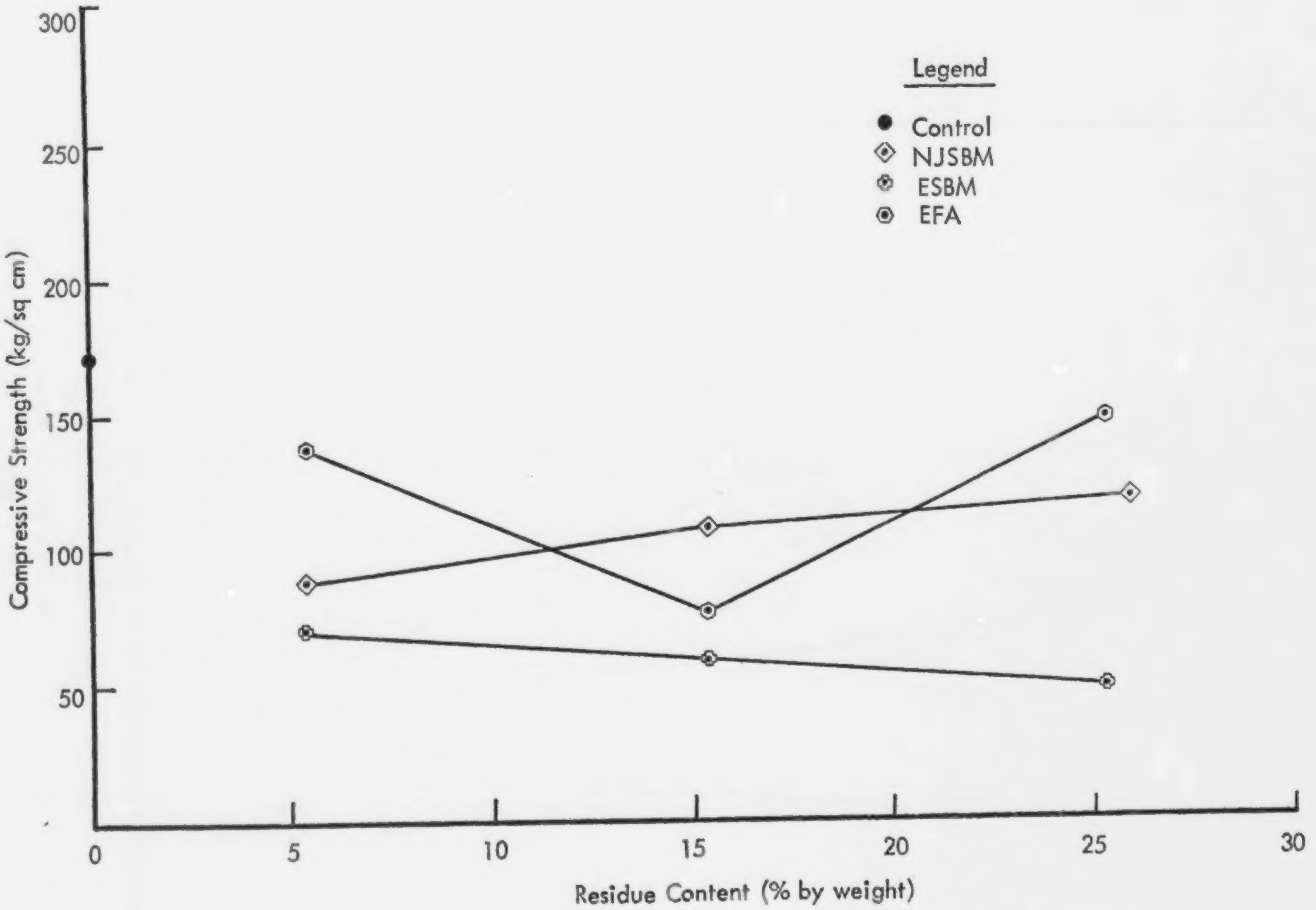

Figure 81. Concrete compressive strength tests: NJSBM, ESBM, EFA after seven day cure.

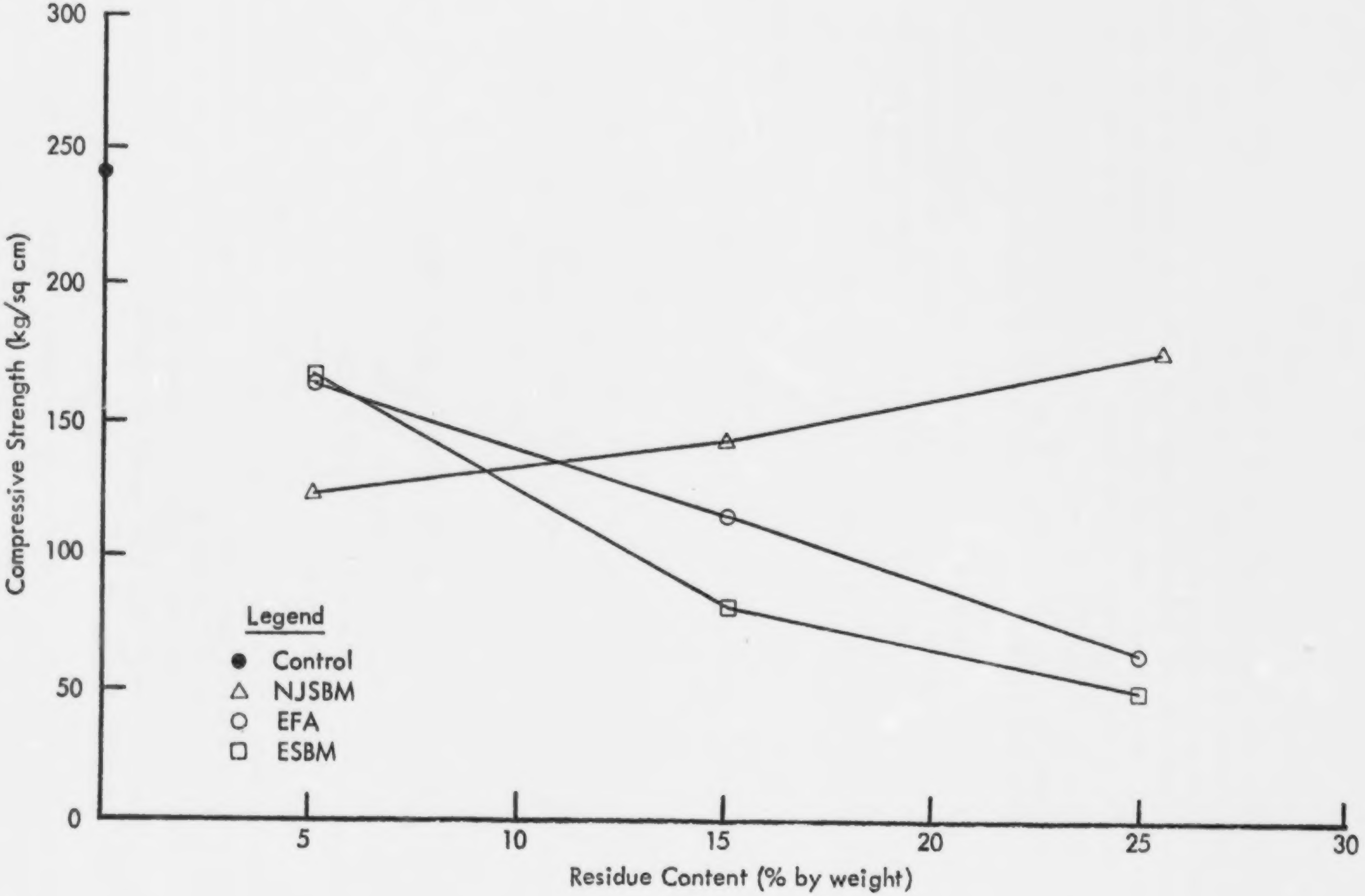

Figure 82. Concrete compressive strength tests: NJSBM, EFA, ESBM after 28 day cure.

Asphalt

Procedure. Residues were tested as replacements for aggregate filler in asphalt. Samples were made and tested for compressive strength following the procedures outlined in ASTM-D-1074; test cylinders were approximately 10 cm in diameter and length. Residue contents tested were 0, 20, 45, 82, and 92 percent of aggregate volume (measured by weight from specific gravities). The aggregate conformed to State of California Department of Transportation 3/8-inch maximum gradation specifications. To simplify handling and to lower test cost, emulsified asphalt (SS-1H) was used in concentrations of 8 to 13 percent by weight. Compression tests were also performed for samples containing portland cement, lime or hydrochloric acid additives. Table 97 summarizes the sample compositions.

All residues were slaked before being added to the asphalt mixtures. Unslaked residues produced poor results, particularly the NJSBM. Reactions between the residue and the emulsified asphalt resulted in a significant decrease in density. In some cases, expansion of the residue was enough to completely disintegrate the test specimen which resulted in a crumbly pile of aggregate and partially coated residue (see Figure 83).

Samples were subjected to a compacting load of 17,199 kg for two minutes. Samples were then measured and coded, and those that were within 10.16 ± 0.64 cm in length were cured in an oven at 60 ± 3°C. One sample of each composition was cured for 29 hours and one for 7 days.

Results. In most cases, substitution of fluidized-bed combustion residues for aggregate did not have a significant beneficial or adverse effect on asphalt compressive strength (see Figures 84 through 87). In some cases, test specimens containing NJSBM showed significantly increased strength (specimens 7-day cure/90 percent residue, and 29-hour cure/45 percent residue). Major reduction in strength also occurred (7-day cure/82 percent NJFA).

Potential Agricultural Application of FBC Residues

Plants, to complete their life cycle development, require some traces of zinc, copper, iron, manganese, chlorine, and aluminum, as well as large quantities of oxygen, carbon, hydrogen, nitrogen, phosphorus, potassium, magnesium, and calcium. The former group of elements is called micronutrients, and the latter, macronutrients. Any material which contains these nutrients in plant-available form has potential value as a soil conditioner. Fluidized-bed fly ash and spent bed residue materials contained most of the micronutrients and some of the macronutrients necessary for plant growth, as shown in Tables 13 to 17 which present the results of the residue chemical characterizations. These residues, because of their compostion and particle size, have excellent potential as a good soil conditioner with considerable nutritive value.

Acidic soils which occur in humid regions (such as the eastern United States), may cause the calcium and magnesium ions to be gradually leached, and farming may accelerate this leaching process. Soil pH is also a major influence in plant growth. Most plants grow

TABLE 97. ASPHALT SAMPLE COMPOSITIONS

Number of Samples	Sample Composition, Percent by Weight			
	Asphalt	Aggregate	Fly Ash or Bed Material	Other Components
12	8	92	--	--
24	8	72	20	--
24	8	47	45	--
24	8	--	92	--
4	8	82	--	10 cement
24	8	--	82	10 cement
4	8	82	--	10 lime
24	8	--	82	10 lime
4	8	92	--	0.24 - 7*HCL
24	8	--	91.76–85	0.24–7* HCL
68				

*Depending on type of residue

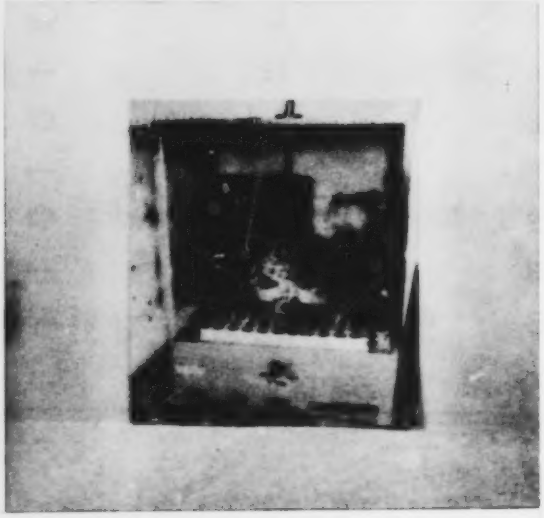

Figure 83 . Result of reaction between residues and emulsified asphalt.

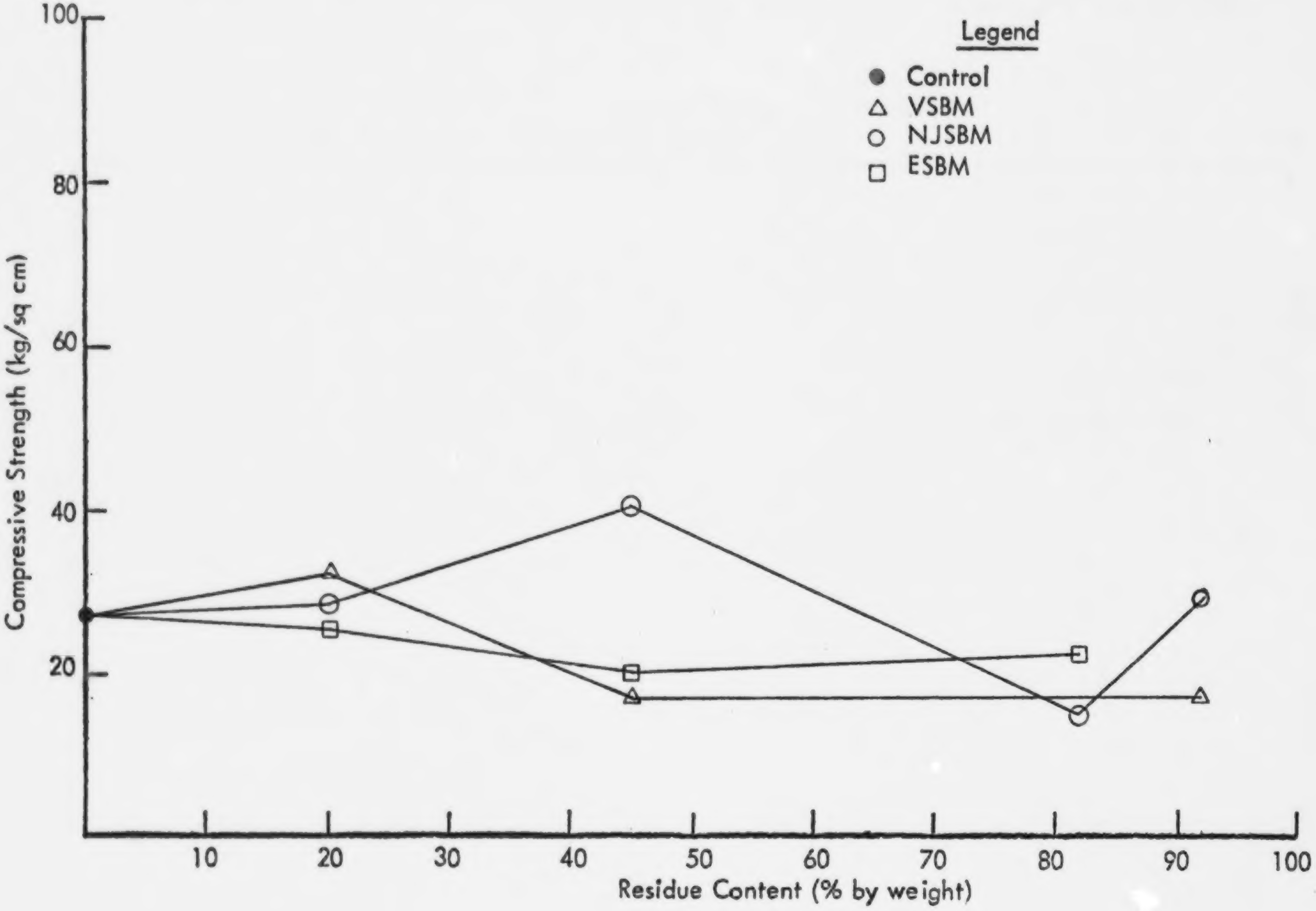

Figure 84. Asphalt compressive strength tests: VSBM, NJSBM, ESBM after 29 hour cure.

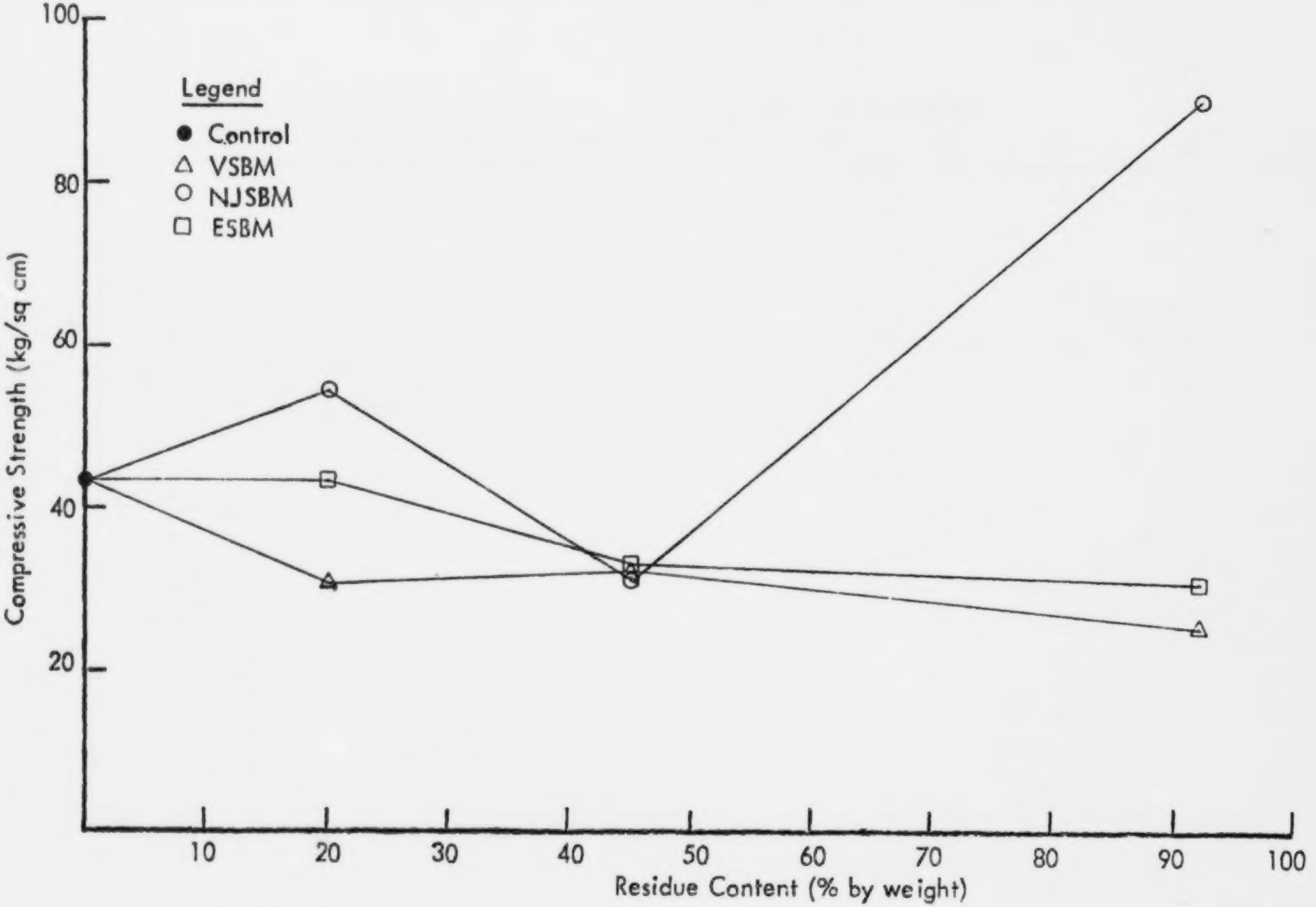

Figure 85. Asphalt compressive strength tests: VSBM, NJSBM, ESBM after seven day cure.

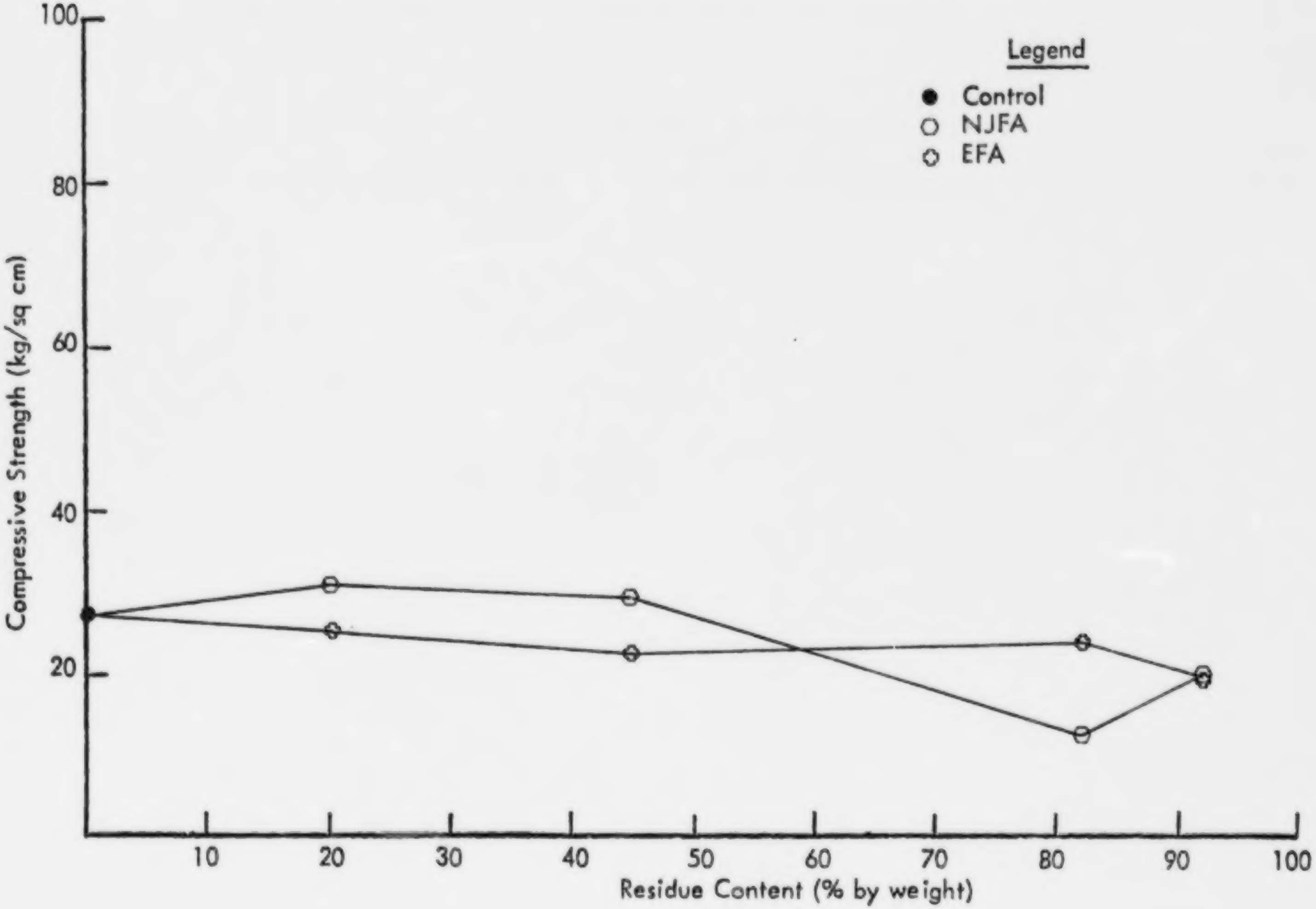

Figure 86. Asphalt compressive strength tests: NJFA, EFA after 29 hour cure.

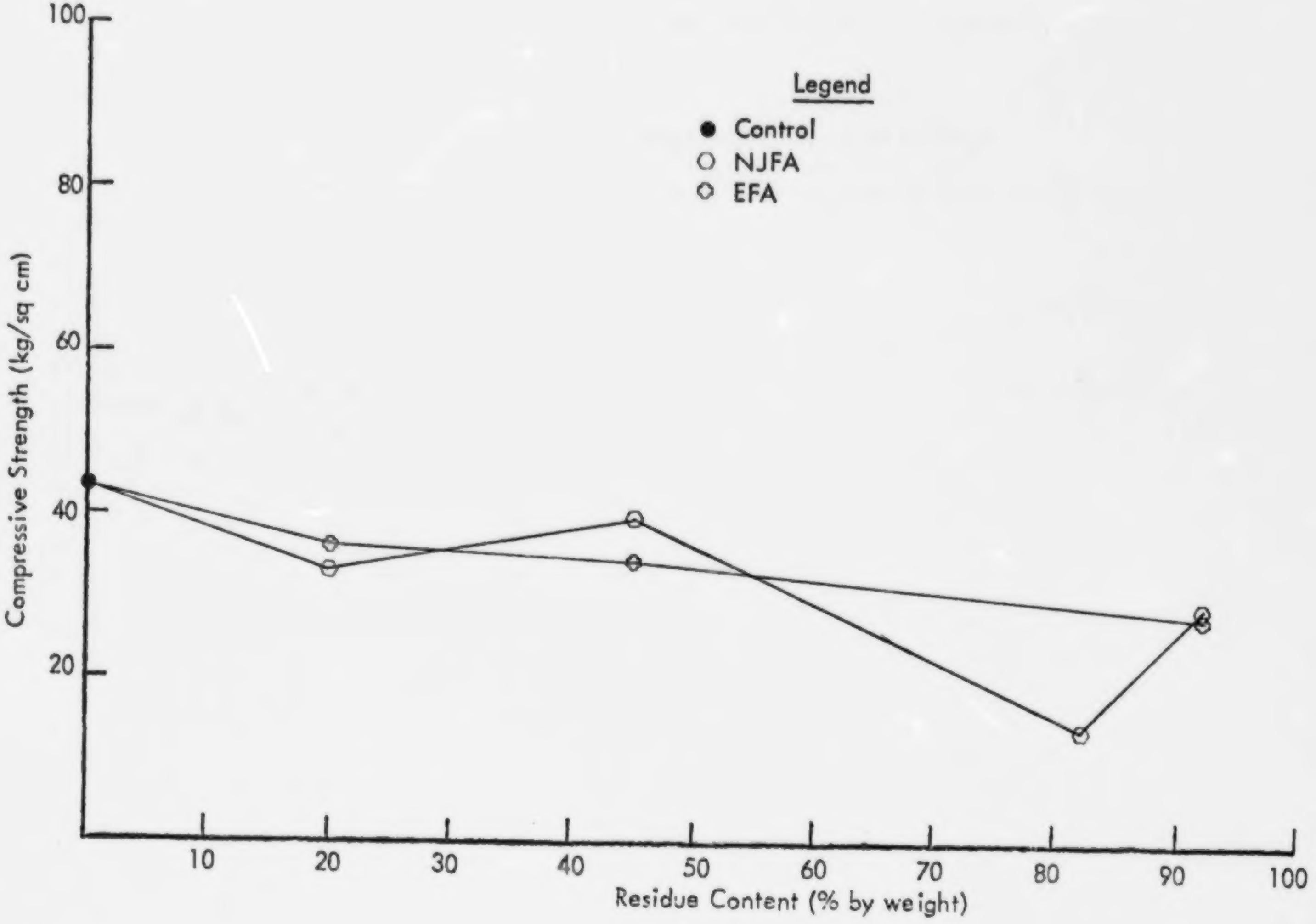

Figure 87. Asphalt compressive strength tests: NJFA, EFA after seven day cure.

best between the range of 7.0 to 7.5, hence, both higher and lower pH's may be detrimental.

In acidic soils, large amounts of iron, aluminum, manganese, copper, lead, cadmium, and zinc may also enter into solution and be adsorbed on the surface of the soil particles in a form that plants can readily assimilate. High levels of soluble manganese, iron, and other metals may interfere with crop growth, but liming can correct this condition. In contrast, molybdenum is more soluble in alkaline soils than in acidic soils, and thus uptake of this micronutrient may be increased with liming. Nevertheless, if soil has a pH greater than 8.0, most of the trace elements are fixed (less soluble) in the soil matrix and are unavailable to plants. Fluidized-bed residues can act as a liming agent and may be used as an excellent soil conditioner to increase the soil pH, reduce soil acidity, and thus lessen the leaching of magnesium and calcium, and prevent excessive uptake of toxic heavy metals to plants.

The potential for residue agricultural applications was evaluated in a series of small-scale preliminary type plant growth tests. Table 98 presents the test program schedule. Maize was also planted and harvested; however, this program was discontinued at the request of the Environmental Protection Agency authorities before analyses of the maize crops were started. Likewise, the analytical evaluation of Experiments 2, 3, and 4 were not completed prior to the Environmental Protection Agency request.

Experiment 1. Cherry Tomatoes

Procedure. Small cubicle plastic pots with about 1.06 cu cm volume were filled with a commercial potting mixture (Supersoil). The average weight of potting mixture used was about 400 grams. The pots were too small to permit the test plants to complete their entire life cycle. Residues were mixed into potting mixture at application rates of 75, 150, 225, and 300 grams per pot, which corresponded to field application rates of 67.2, 134.4, 201.7, and 268.9 kkg per hectare. Six residues were tested: CFA, FSA, VFA, VSBM, NJFA, and NJSBM (these are identified in Chapter 1, Table 6). There were eight pots per residue and two control pots. Fertilizer was surface-applied to each of the soil/residue (and control) mixtures: one gram of ammonium sulfate as a source of nitrogen and one gram of monobasic potassium phosphate as a source of phosphate and potassium. These fertilizers were applied in two equal doses of 0.5 grams each. The first application was made two weeks after planting, and the second, four weeks after planting.

Germinated cherry tomato seeds were planted (3 March 1976), and several plants germinated; each pot was subsequently thinned to one plant per pot. There were two replications for each residue application rate; this was done to reduce the impact of genetic and environmental variability on the test results. The tomato plants were irrigated once a week. The plants were harvested on May 7, 1976.

Results

Photographs of the harvested tomato plants were presented in the first annual report (T_1

TABLE 98 . PLANTING SCHEDULE FOR AGRICULTURAL TESTS

No.[a,b]	Date of Planting	Date of Harvesting	Crop	Residue/Soil Weight (g/400 g of soil, dry wt)	Remarks
1	27 March 1976	7 May	Tomato[c]	75,150,225,300	Completed
2–A	12 June	29 July	Tomato[c]	2.5,12.5,25.0,37.5	Completed
2–B	18 August	15 February, 1977	Tomato[c]	None added	Evaluate effects of single addition on second rotation
3	15 January 1977	7 March	Spinach[d]	2.5,7.5,10.0,12.5	Crop had high salt tolerance and edible leaves
4	1 February	30 March 1977	Lettuce f,g	2.5,7.5,10.0,12.5	

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[a] Numerals refer to a given set of pots in which crops were planted sequentially; letters refer to specific rotation in any given set of pots.

[b] Six residues were tested (CFA, FSFA, NJFA, NJSBM, VFA, VSBM), with one set of pots for each residue type, and one set as a control. 1,000 cu cm pots were used.

[c] Cherry tomatoes.

[d] Green leaf spinach.

[e] EFA and ESBM residues were tested, rather than CFA, FSFA residues.

[f] Green leaf lettuce.

represented the lowest application rate, and T_4, the highest). No pictures were shown of CFA or FSFA because the tomato plants did not grow at all in those fluidized-bed oil gasification residues. The very high soil pH produced by the residues significantly suppressed root development for all residues at all application rates. Also, plant growth was significantly less for the test plants than for the controls, and higher application rates were associated with reduced growth. From this experiment it was concluded that (1) there were differences among the six residues in their effects on plant growth, and (2) at these high application rates, there were significant negative impacts on plant growth and root development. Based on these conclustions, a second experiment was devised to test the impact of lower application rates.

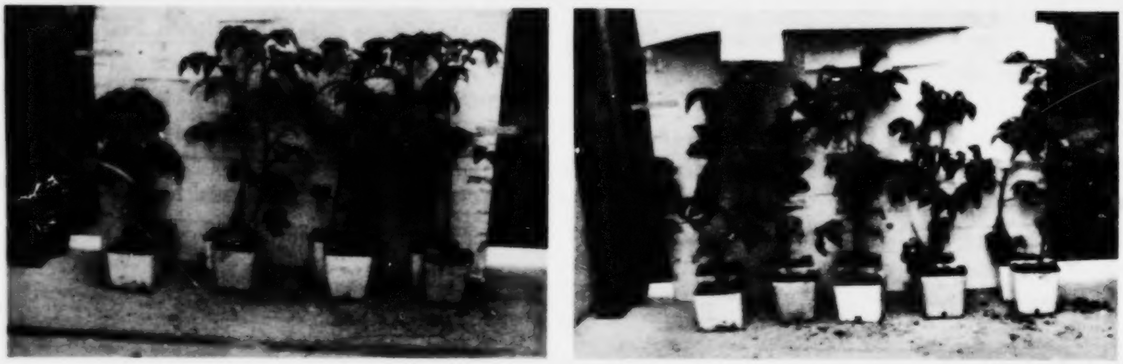
Experiment 2-a. Cherry Tomatoes

Procedure. This experiment was identical to the previous one, except as noted. Application rates were 2.5, 12.5, 25.0, and 37.5 grams per pot, corresponding to field application rates of 2.2, 11.2, 22.4, and 33.6 kkg per hectare. Three replications were performed for each application rate and two controls. There were seventy-four pots used in total. Fertilizer was applied as above, and the plants were irrigated once per week, with the exception that during the first three weeks exceptionally warm weather required irrigation twice per week. Planting occurred on 12 June 1976, and harvesting on 29 July 1976. Above-ground plant tissues were digested and analyzed following the procedures referenced in Appendix A.

Results. Photographs taken of the test plants just before harvesting are shown in Figure 88. The impact of residue application on plant growth is given quantitatively in Table 99, and graphically in Figures89 and 90 . Table 99 also presents the wet and dry weight and the ratio of wet to dry weight.

The results indicated that there was significant improved growth response at equivalent application rates of 2.2 and 11.2 kkg per hectare for CFA, FSFA, VFA, and NJFA residues. For these same residue types, growth was repressed at excessive application rates equivalent growth response at all the application rates tested for the VSBM, and NJSBM residues. Plant tissue percent dry weight increased from 5 to 80 percent with all residue types for equivalent application rates of 2.2 and 11.2 kkg per hectare. For CFA, the percent dry weight of plant tissue decreased significantly at a 22.4 kkg per hectare application rate in relation to the control plantings.

The standard commercial potting mixture used in the experiments had a high level of humic acid with, consequently, a low pH (about 5.5). Since the fly ash and spent bed residues were quite alkaline, adding them to the potting mixture raised the soil pH (as shown in Tables 100and 101). The effect on plant growth plotted against soil pH is presented in Figure 91 . This latter figure shows the growth improvements (in comparison to the control plantings when the pH was in the normal range from 6.2 - 7.8. This growth improvement is almost certainly partially the result of the residues having increased the pH to more optimal values and providing adsorption of desirable trace elements.

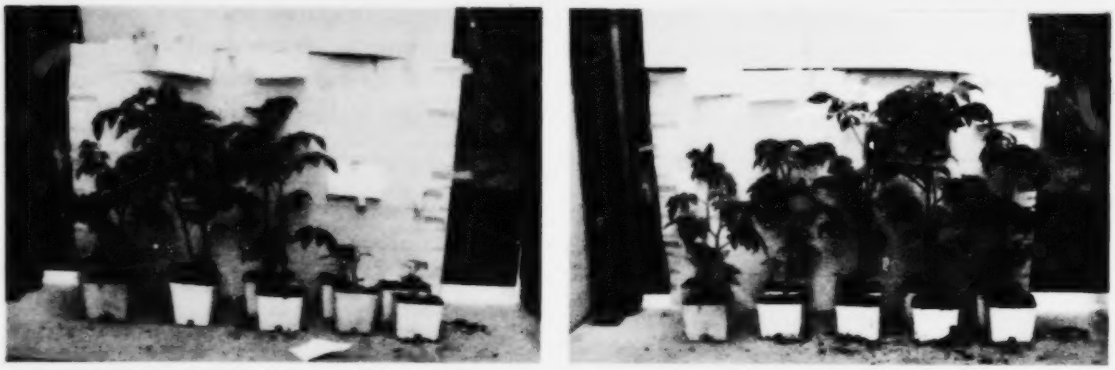


Control T_1 T_3 T_4

PER, Virginia fly ash

Control T_1 T_2 T_3 T_4

PER, Virginia spent bed material

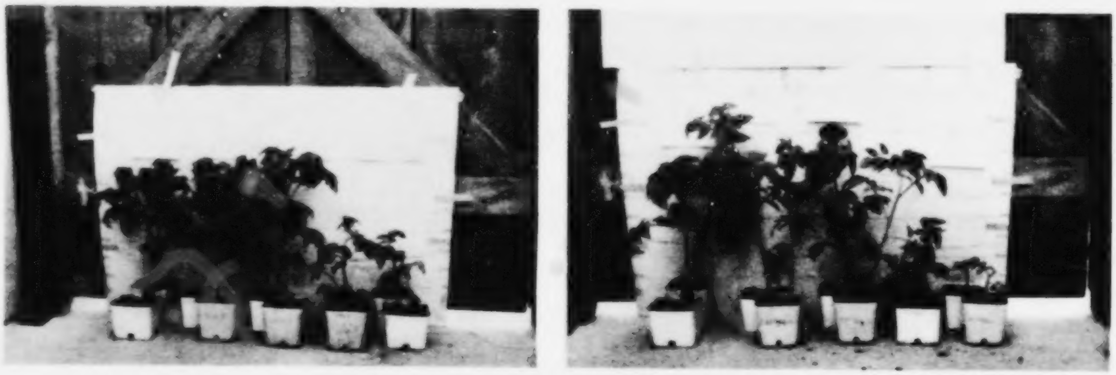


Control T_1 T_2 T_3 T_4

Exxon, New Jersey fly ash

Control T_1 T_2 T_3 T_4

Exxon, New Jersey spent bed material



Control T_1 T_2 T_3 T_4

Esso, England cyclone fly ash

Control T_1 T_2 T_3 T_4

Esso, England fines, stack fly ash

Figure 88 . Experiment 2-A, tomato plant growth.

TABLE 99. EXPERIMENT 2-A: TOMATO PLANT GROWTH RESULTS

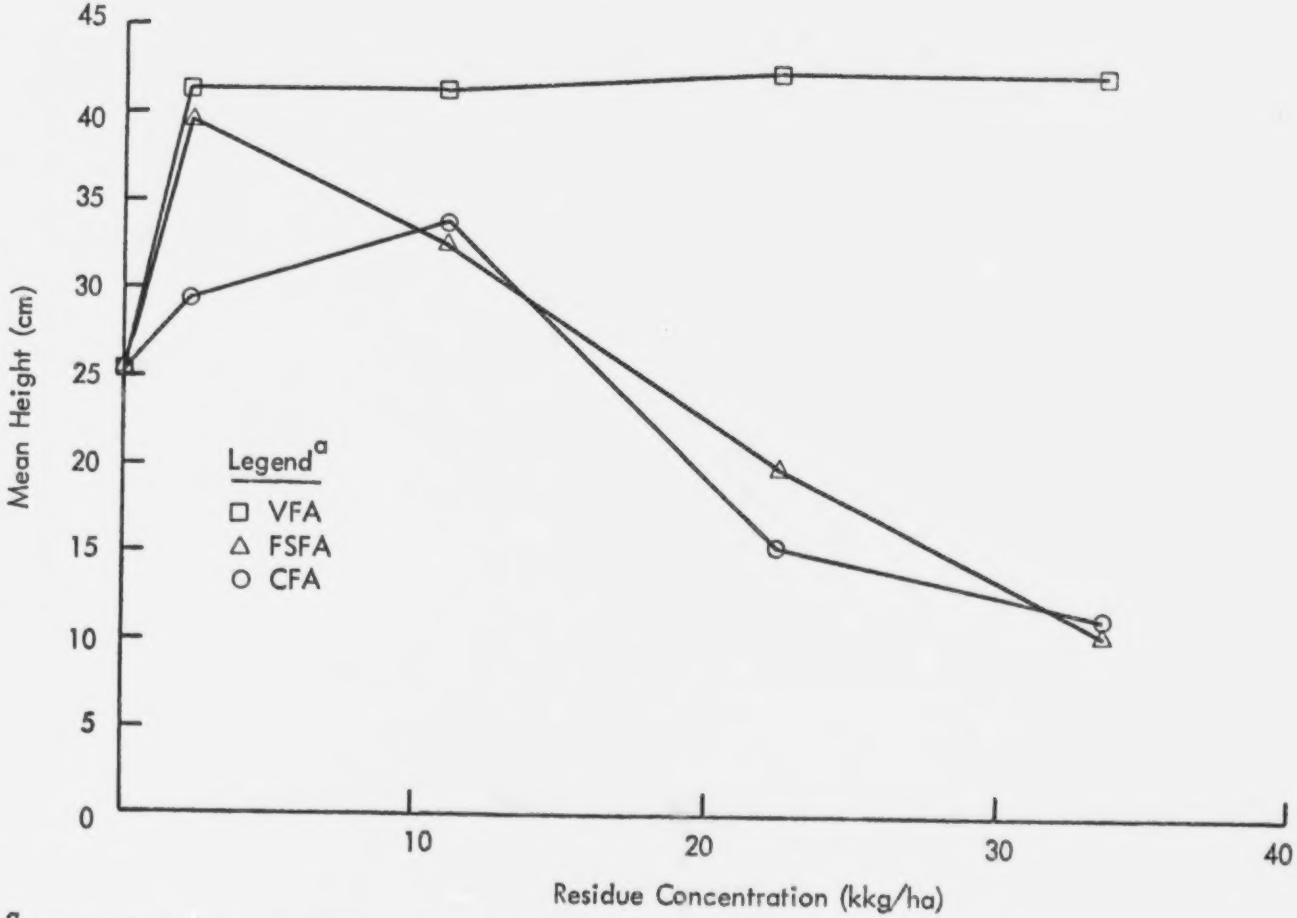
Treatment Code[a]	Application Rate (kkg/ha)	Plant Height (cm)			Mean Height (cm)	Green Weight of Shoots (g)	Dry Weight of Shoots (g)	Ratio of Dry to Wet Weight (%)
		R_1[b]	R_2[b]	R_3[b]				
Control	0	31	28	17	25.3	40.0	3.5	8.75
CFA	2.2	30	30	29	29.6	31.1	4.9	16.55
	11.2	34	33	35	34.0	57.5	5.2	15.29
	22.4	15	20	11	15.3	11.4	0.7	4.57
	33.6	5	16	13	11.3	5.3	0.5	9.43
FSFA	2.2	33	35	41	39.6	62.0	5.5	13.88
	11.2	27	35	36	32.6	55.0	4.7	14.41
	22.4	19	22	19	20.0	15.0	1.4	7.01
	33.6	14	9	8	10.3	13.0	0.9	8.73
VFA	2.2	36	43	45	41.3	48.8	5.6	13.55
	11.2	37	43	45	41.3			
	22.4	36	43	47	42.6	60.2	6.3	10.46
	33.6	43	37	43	42.3	64.3	4.2	6.53
VSBM	2.2	43	45	40	42.6	64.4	6.4	9.93
	11.2	39	40	41	40.6	61.6	5.7	9.25
	22.4	35	35	36	35.3	28.3	1.9	6.71
	33.6	35	43	37	38.7	40.0	3.7	9.25

(continued)

TABLE 98 (Cont.)

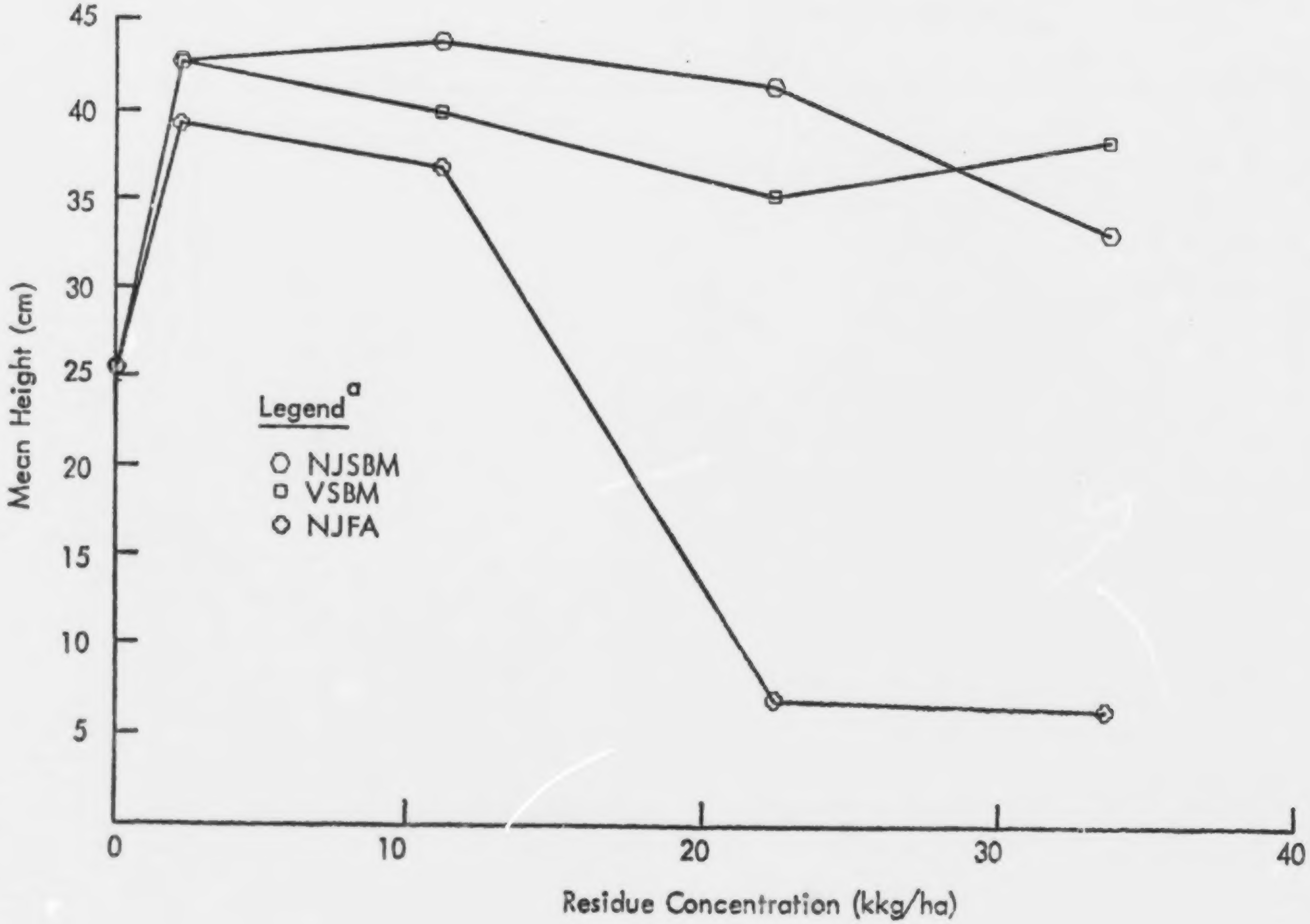
Treatment Code[a]	Application Rate (kkg/ha)	Plant Height (cm)			Mean Height (cm)	Green Weight of Shoots (g)	Dry Weight of Shoots (g)	Ratio of Dry to Wet Weight (%)
		R_1[b]	R_2[b]	R_3[b]				
NJFA	2.2	43	36	39	39.3	55.1	5.4	9.80
	11.2	33	40	34	37.0	38.7	3.4	8.78
	22.4	10	8	3	7.0	3.9	0.3	7.69
	33.6	5	8		6.5	4.8	0.4	8.33
NJSBM	2.2	37	39	42	39.3	35.6	3.0	7.63
	11.2	45	43	44	44.0	35.2	3.0	8.52
	22.4	43	45	37	41.6	75.9	6.0	7.90
	33.6	37	32	30	33.3	33.6	3.2	9.52

[a] Residue source code presented in Table 6.
[b] Replicate



[a] See Table 6 for explanation of letter code.

Figure. 89 . Mean tomato plant height, Experiment 2: VFA, FSFA, CFA .



[a] See Table 6 for explanation of letter code.

Figure 90 . Mean tomato plant height: Experiment 2: NJSBM, VSBM, NJFA.

TABLE 100. pH OF SOIL-RESIDUE MIXTURE

Treatment Code[a]	Application Rate (kkg/ha)	Soil pH[b]			
		R_1[c]	R_2[c]	R_3[c]	Mean
Control	0	5.52	5.62	5.55	5.56
CFA	2.2	7.01	7.23	7.20	7.14
	11.2	7.43	7.22	7.32	7.32
	22.4	6.91	7.72	7.70	7.44
	33.6	7.71	7.62	7.81	7.71
FSFA	2.2	7.07	7.01	7.20	7.09
	11.2	7.72	7.51	7.73	7.65
	22.4	7.53	7.72	8.20	7.81
	33.6	8.22	10.32	9.73	9.42
VFA	2.2	7.52	8.49	7.62	7.87
	11.2	7.18	6.82	7.64	7.21
	22.4	7.59	7.81	6.48	7.29
	33.6	7.11	7.83	6.31	7.08
VSBM	2.2	6.33	6.91	6.81	6.68
	11.2	8.21	7.26	7.56	7.67
	22.4	8.73	7.51	7.92	8.05
	33.6	7.91	7.75	7.72	7.79
NJFA	2.2	6.83	6.50	6.42	6.58
	11.2	7.80	7.69	7.25	7.58
	22.4	8.29	8.51	8.21	8.33
	33.6	7.42	8.50	6.81	7.57
NJSBM	2.2	[illegible]	7.62	6.91	7.75
	11.2	7.[illegible]	8.01	7.68	7.67
	22.4	6.61	8.11	8.39	7.70
	33.6	6.63	6.42	7.42	6.82

[a] Residue source code presented in Table 6.
[b] Soil and water mixed in 1:1 ratio.
[c] Replicate

TABLE 101. pH OF SOIL RESIDUE MIXTURE AFTER CROP 2 HARVEST

Treatment Code[a]	Application Rate (kkg/ha)	Soil pH[b]			
		R_1[c]	R_2[c]	R_3[c]	Mean
Control		6.7	7.1	6.9	6.90
CFA	2.2	6.73	6.70	7.30	6.91
	11.2	7.54	6.90	7.10	7.18
	22.4	7.17	7.60	7.40	7.39
	33.6	7.13	7.80	8.20	7.90
FSFA	2.2	7.21	7.20	6.80	7.07
	11.2	7.80	7.60	7.40	7.60
	22.4	8.04	8.00	7.00	7.68
	33.6	8.33	7.50	8.50	8.11
VFA	2.2	7.14	7.60	7.40	7.38
	11.2	6.34	7.10	6.90	6.78
	22.4	7.15	6.80	7.20	7.05
	33.6	6.76	6.30	6.20	6.42
VSBM	2.2	5.90	6.60	6.40	6.30
	11.2	7.36	6.64	7.33	7.11
	22.4	7.82	6.71	7.43	7.32
	33.6	7.31	7.33	7.42	7.35
NJFA	2.2	7.27	6.70	7.30	7.09
	11.2	7.75	7.0	7.0	7.25
	22.4	8.30	8.0	7.70	8.00
	33.6	6.20	6.50	6.50	6.40
NJSBM	2.2	6.24	6.12	6.21	6.19
	11.2	6.81	7.13	6.82	6.92
	22.4	7.66	7.10	6.90	7.22
	33.6	7.35	7.60	7.50	7.45

[a] Residue source code presented in Table 6.
[b] Soil and water mixed in 1:1 ratio.
[c] Replicate

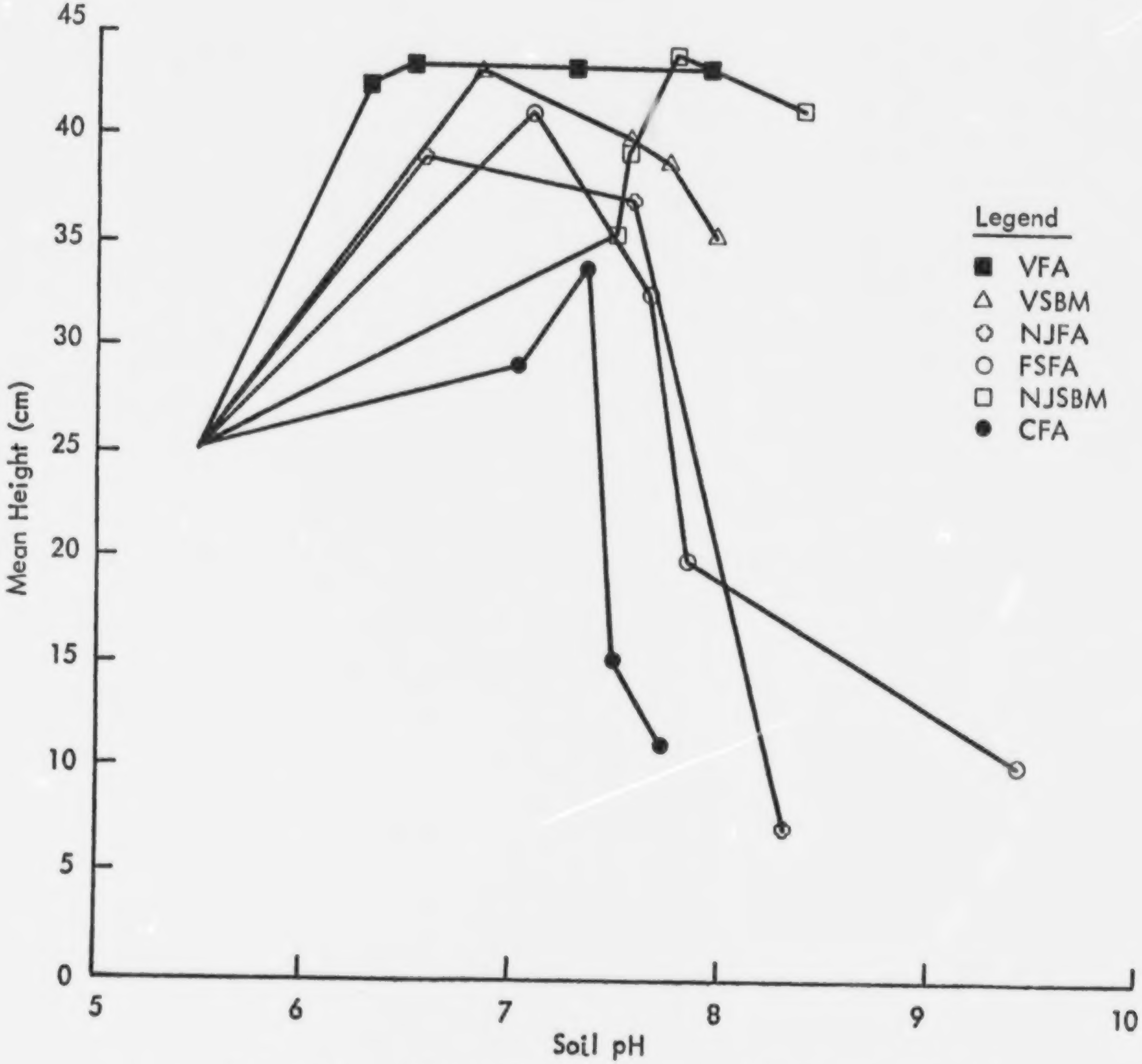


Figure 91 . Tomato plant growth vs. soil pH, Experiment 2-A.

The biodegradation of the residue materials by soil microorganisms may also have released micronutrients for plant uptake. If the pH adjustment mechanism were beneficial, one would expect it would make little difference what type and source of fluidized-bed residue were used. But, as Figure 91 shows, there is considerable variability in plant tissue analytical results for a given pH. Since the various residues differ substantially in chemical composition, it may be tentatively assumed that this dispersion reflects differences in the availability and quantity of nutrients that were provided to the test plants in the residues.

Results for chemical analyses of plant tissues are given in Table 102. Those results which show significant variability are graphically represented in Figures 92 to 95 . Tomato plants test-grown on residue-treated soil showed significantly lower concentrations of analyzed levels for heavy metals than the control plants. This effect is undoubtedly pH-related In contrast, for the most part, sulfate concentrations were not significantly different with residue-treated or control test soil plantings. Exceptions were FSFA/T_2, VFA/T_4, NJFA/T_2, and NJSBM/T_1, T_3, and T_4. There was no significant difference in the concentration of magnesium between the control and residue-treated soil growth except for NJFA/T_2. All residue-treated vegetation (except VFA/T_3) showed significantly higher concentrations of calcium, which was associated with cell turgidity. Although the calcium concentration was higher in the treated plants, they did not show signs of toxic calcium levels.

Experiment 2-B. Cherry Tomatoes

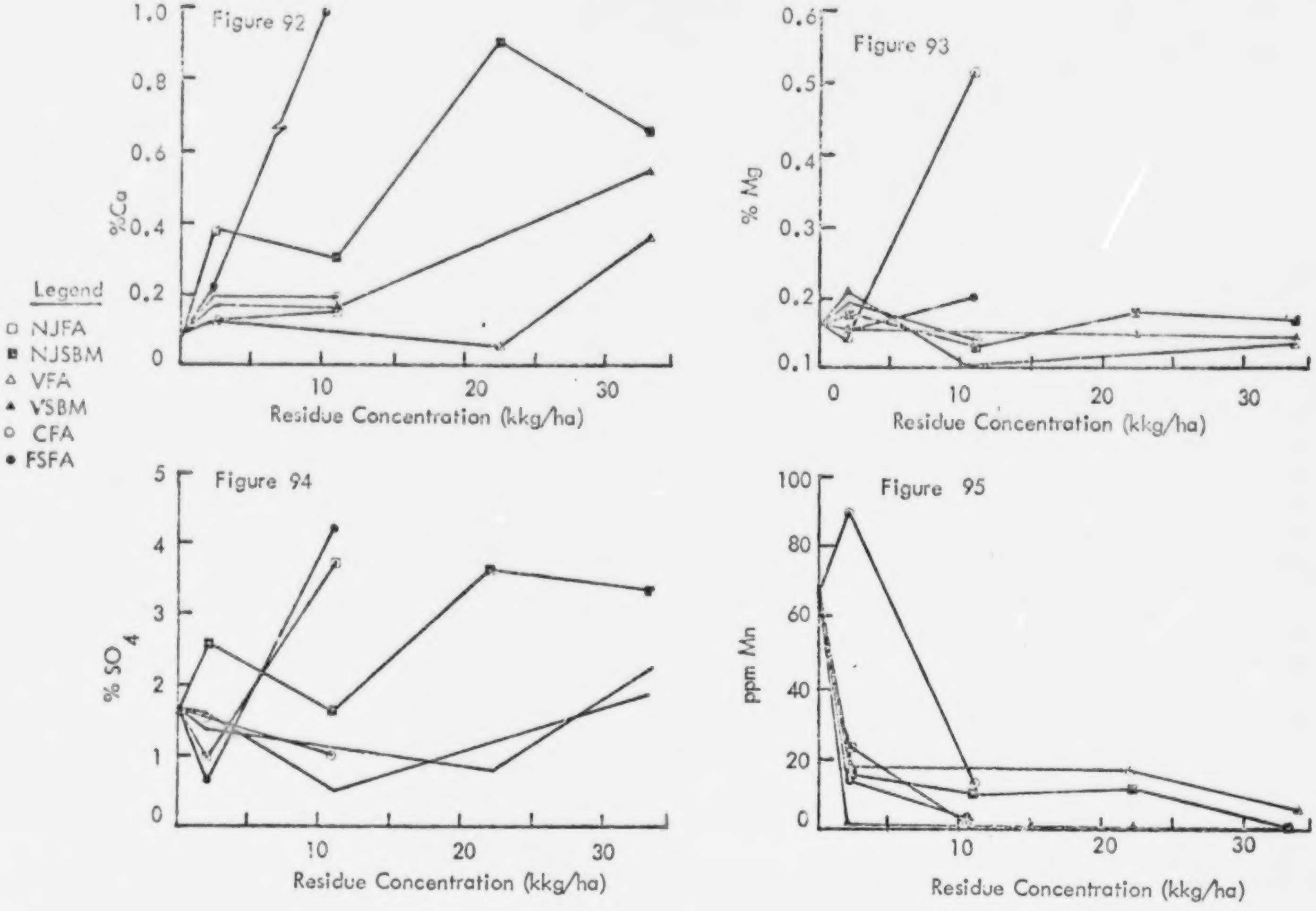
Procedure. Germinated cherry tomato seeds were replanted in the same pots of soil used in Experiment 2-A. No further application of residues was provided so that the effects of a single addition of residue on a second crop planting could be evaluated. Because Experiment 2-A showed significant improved growth response at equivalent application rates of 2.2 and 11.2 kkg per hectare, the experiment was limited to these two latter equivalent application rates. Tomato planting was perfomed on August 18, 1976, and harvesting occurred on February 15, 1977. All other aspects of Experiment 2-B were similar to Experiment 2-A.

Results. Results of the plant tissues' chemical analyses are tabulated in Table 103. Some of the results, showing wide variability for different added residues are graphically illustrated in Figures 96 to 103. The calcium contents for all the residue-treated crops were generally equal to or lower in concentration than the control crops. With only one exception, the calcium concentrations were lowest in the plants grown in the soil containing the equivalent of 2.2 kkg of residues per hectare. The calcium content in the VSBM residue continued to decrease in the soil containing the equivalent of 11.2 kkg of residue per hectare. Magnesium showed no significant difference in concentration between the control and the residue-treated test vegetation, except for NJSBM/T_2, which showed a significant reduction in magnesium concentration.

Likewise, the concentration of cadmium and copper generally was not significantly different between the control and the residue-treated test tomato plants. The only exceptions were plants grown for CFA/T_2 and VFA/T_1 and T_2 soil mixtures; these plants contained a much higher concentration of cadmium than the control plants did. With the exception of CFA/T_2,

TABLE 102. EXPERIMENT 2-A : TOMATO PLANT TISSUE, CHEMICAL ANALYSIS

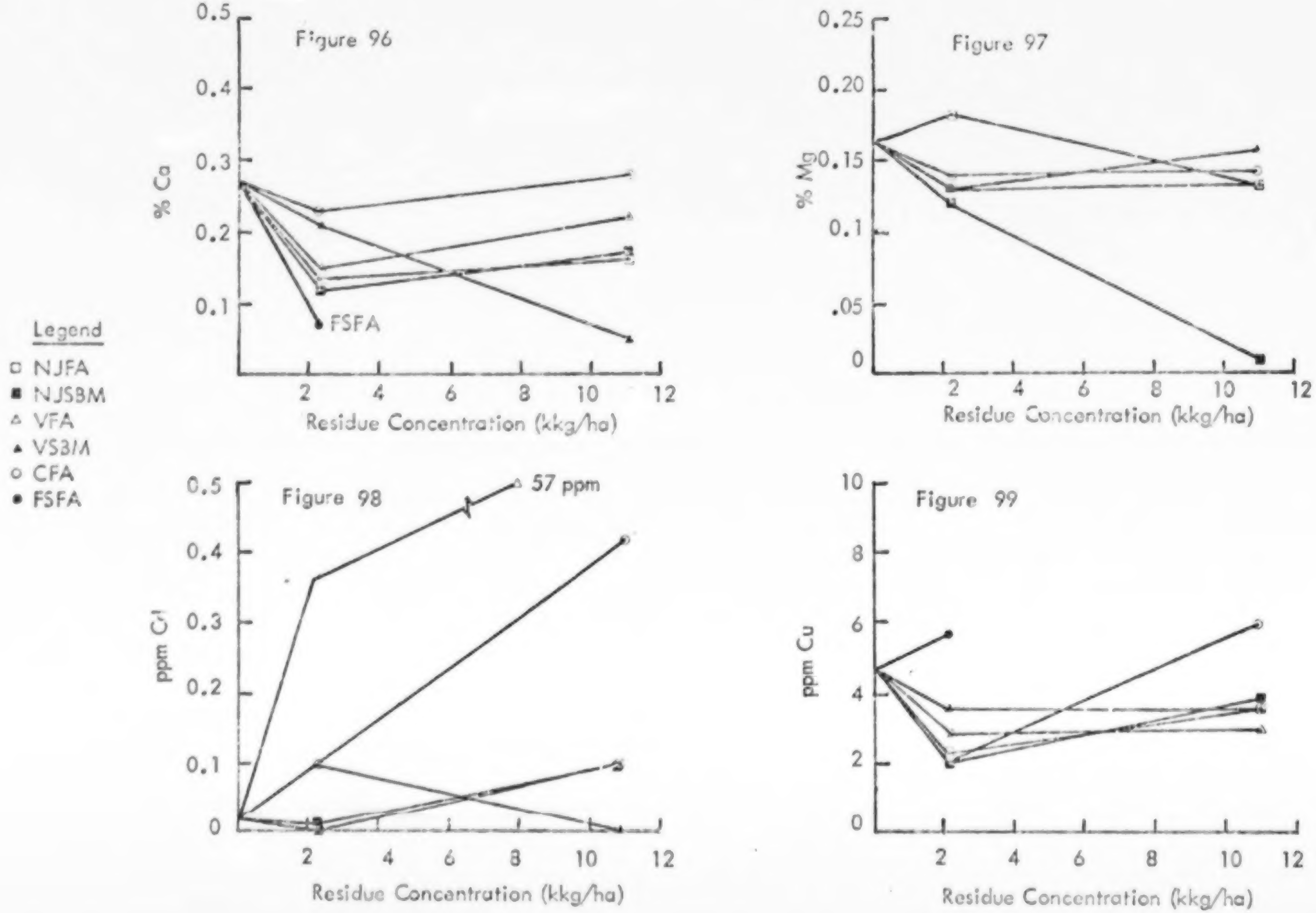
Treatment (residual code)	Application Rate (kkg/ha)	Constituents									
		Ca	Mg	SO_4	Cd	Cu	Fe	Mn	Pb	Zn	Ag
		(%)			ppm						
Control	0	0.08	0.158	1.65	--	--	130	68	--	51	--
CFA/T_1	2.2	0.19	0.197	1.50	--	--	90	93	--	20	--
T_2	11.2	0.19	0.145	1.00	--	--	N.D.	14	--	2	--
FSFA/T_1	2.2	0.22	0.155	0.60	--	--	N.D.	3	--	20	--
T_2	11.2	1.22	0.202	4.30	--	--	N.D.	14	--	2	--
NJFA/T_1	2.2	0.12	0.135	0.90	--	--	70	22	--	6	--
T_2	11.2	0.15	0.523	3.75	--	--	N.D.	N.D.	--	0.1	--
NJSBM/T_1	2.2	0.38	0.182	2.60	--	--	20	16	--	1	--
T_2	11.2	0.30	0.130	1.60	--	--	20	10	--	1	--
T_3	22.4	0.86	0.178	3.70	--	--	N.D.	12	--	N.D.	--
T_4	33.6	0.66	0.170	3.40	--	--	20	N.D.	--	4	--
VFA/T_1	2.2	0.12	0.153	1.40	--	--	90	18	--	10	--
T_3	22.4	0.05	0.151	0.80	--	--	30	17	--	5	--
T_4	33.6	0.37	0.148	2.30	--	--	30	6	--	4	--
VSBM/T_1	2.2	0.17	0.211	1.60	--	--	N.D.	N.D.	--	2	--
T_2	11.2	0.16	0.102	0.50	--	--	40	N.D.	--	7	--
T_4	33.6	0.56	0.140	1.90	--	--	60	N.D.	--	3	--



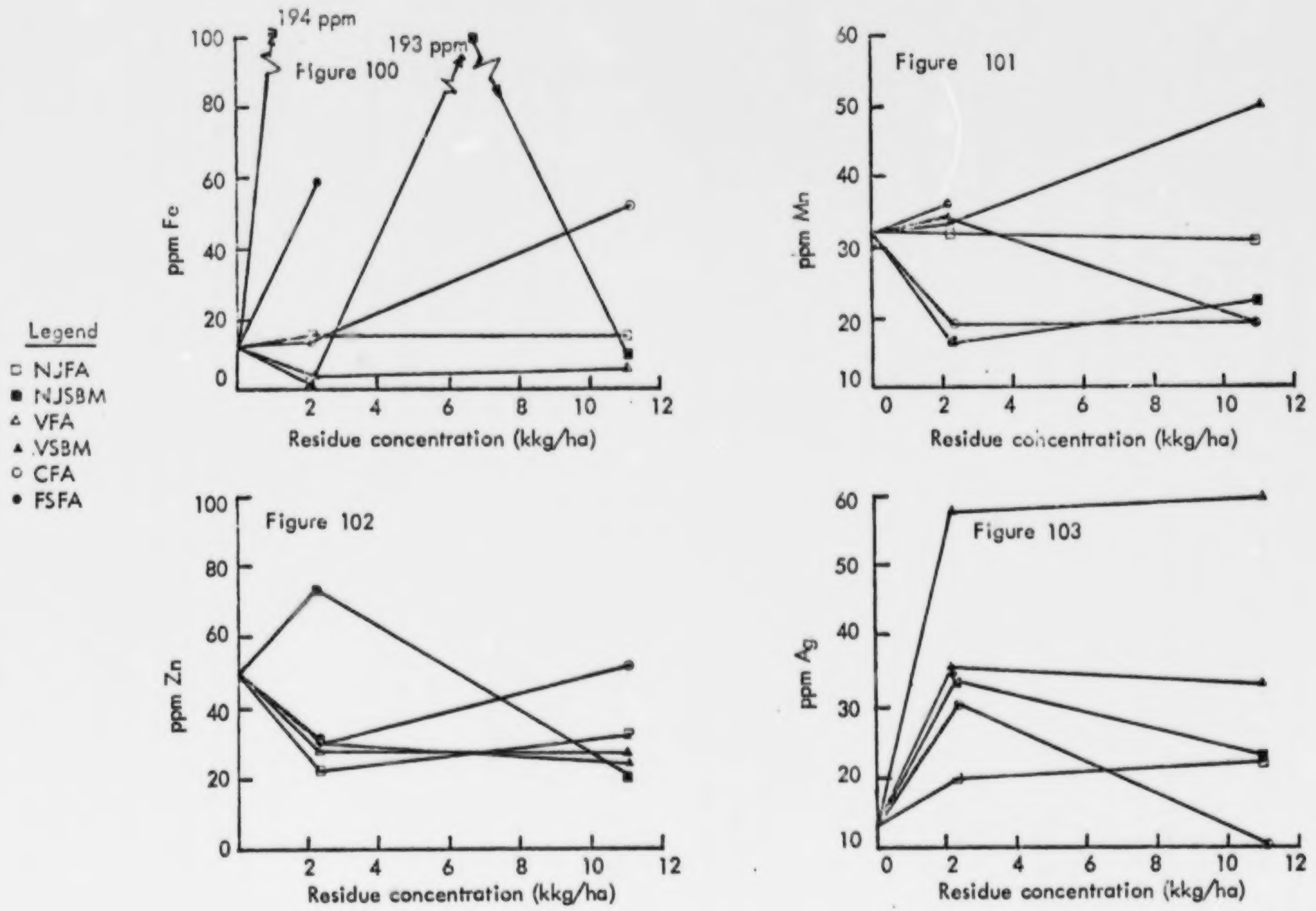
Figures 92 to 95. Experiment 2-A: Analytical results of calcium, magnesium, sulfate, and managanese.

TABLE 103. EXPERIMENT 2-B: TOMATO PLANT TISSUE, CHEMICAL ANALYSIS

Treatment (residual code)	Application Rate (kkg/ha)	Constituents									
		Ca	Mg	SO_4	Cd	Cu	Fe	Mn	Pb	Zn	Ag
		(%)			ppm						
Control	0	0.27	0.166	--	0.07	4.8	11.3	32.6	N.D.	49.7	1.3
CFA/T_1	2.2	0.23	0.140	—	0.10	2.0	12.8	19.4	N.D.	30.2	3.1
T_2	11.2	0.28	0.146	—	0.42	6.0	53.3	19.5	7.0	52.5	1.0
FSFA/T_1	2.2	0.07	0.134	--	N.D.	5.8	57.8	36.7	N.D.	30.9	3.5
NJFA/T_1	2.2	0.13	0.186	--	N.D.	2.3	15.1	32.5	N.D.	23.2	2.0
T_2	11.2	0.16	0.136	--	0.10	3.5	15.4	31.6	N.D.	32.7	2.2
NJSBM/T_1	2.2	0.12	0.122	--	0.05	2.0	194	16.7	N.D.	73.2	3.4
T_2	11.2	0.17	0.010	--	0.10	3.8	8.1	25.5	N.D.	21.5	2.3
VFA/T_1	2.2	0.15	0.129	--	0.37	2.8	3.1	33.4	2.2	28.3	5.8
T_2	11.2	0.22	0.134	--	0.57	3.0	5.3	50.5	N.D.	27.6	6.0
VSBM/T_1	2.2	0.21	0.132	--	0.10	3.5	1.2	34.3	N.D.	30.9	3.6
T_2	11.2	0.05	0.160	--	N.D.	3.5	193	19.4	N.D.	26.6	3.3



Figures 96 to 99. Experiment 2-B: Analytical results of calcium, magnesium, sulfate, and manganese.



Figures 100 to 103. Experiment 2-B: Analytical results of iron, manganese, zinc, and silver.

FSFA/T_1, NJSBM/T_1, and VSBM/T_2, the vegetation containing the residue was nearly equal to or lower in iron concentration than the control test vegetation. The exceptions were NJSBM/T_1 and VSBM/T_2 which contained relatively high concentrations of iron at 194 mg/l and 193 mg/l, respectively. This is approximately a 17-fold greater iron concentration than in the first cropping (see Experiment 2-A). The sharp rise in iron concentration may have been due to a possible decrease in pH. Lead was not detected in any of the plant samples except CFA/T_2 and VFA/T_1. Except for NJSBM/T_1, the zinc concentrations in the plant samples grown in the residue enriched soil, were nearly equal to or less than the tomatoes grown in the control soil. Silver concentration in the enriched soil test plants was greater than the control in all but the CFA/T_2 residue mixture.

In general, the second crop growth (Experiment 2-B) showed test results similar to the original crops (Experiment 2-A). A significant difference was noted in the concentration of calcium. In the original test growth, the tomato plants took up more calcium in the residue-treated soil than in the control soil. In the second test planting, the calcium uptake was less in the residue-treated tomato plants than in the control vegetation. Other differences include a general decrease in the magnesium concentration, and a general increase in the iron, manganese, and zinc concentrations during the second test planting of tomatoes. The increases may have been due to a gradual decrease in the pH of the soil. It should be pointed out, however, that the concentrations of these minerals in the residue-treated plants were generally still less than the plants grown in the control test potting soil.

Experiment 3. Spinach

Procedure. The procedure for this experiment was identical to Experiment 2-A, except for the following modifications. The residue application rates in the test soils were further reduced. Thus, the application rates were 2.5, 7.5, 10.0, and 12.5 grams per pot, which corresponded to equivalent field application rates of 2.2, 6.7, 9.0, and 11.2 kkg per hectare. These rates are identified as T_1, T_2, T_3, and T_4, respectively. Germinated spinach seeds were planted on January 15, 1977, and harvested on March 7, 1977. The harvested leaves were digested and analyzed according to the procedures referenced in Appendix A.

Results. The analytical results are tabulated in Table 104, and the results illustrating significant variations between residues are graphically represented in Figures 104 to 109. The analyses of the spinach leaves showed trends similar to that found with tomato plants. That is, concentrations of the minerals were generally lower in the residue-treated test crops than in the control crop. The concentrations of manganese, zinc, molybdenum, and silver were all lower in the residue-treated spinach than in the spinach grown in the control soil. Similarly, the spinach grown in the residue-enriched soil showed concentrations of sodium and aluminum generally equal to or less than the spinach grown in the control soil. Significantly, the concentrations of potassium, barium, and chromium were generally higher in the residue-treated test spinach. In fact, CFA/T_2 contained about seven times the potassium levels found in the control plant. Further, calcium was equal to or less in the test spinach grown in the residue applied at the equivalent rate of 2.2 kkg per

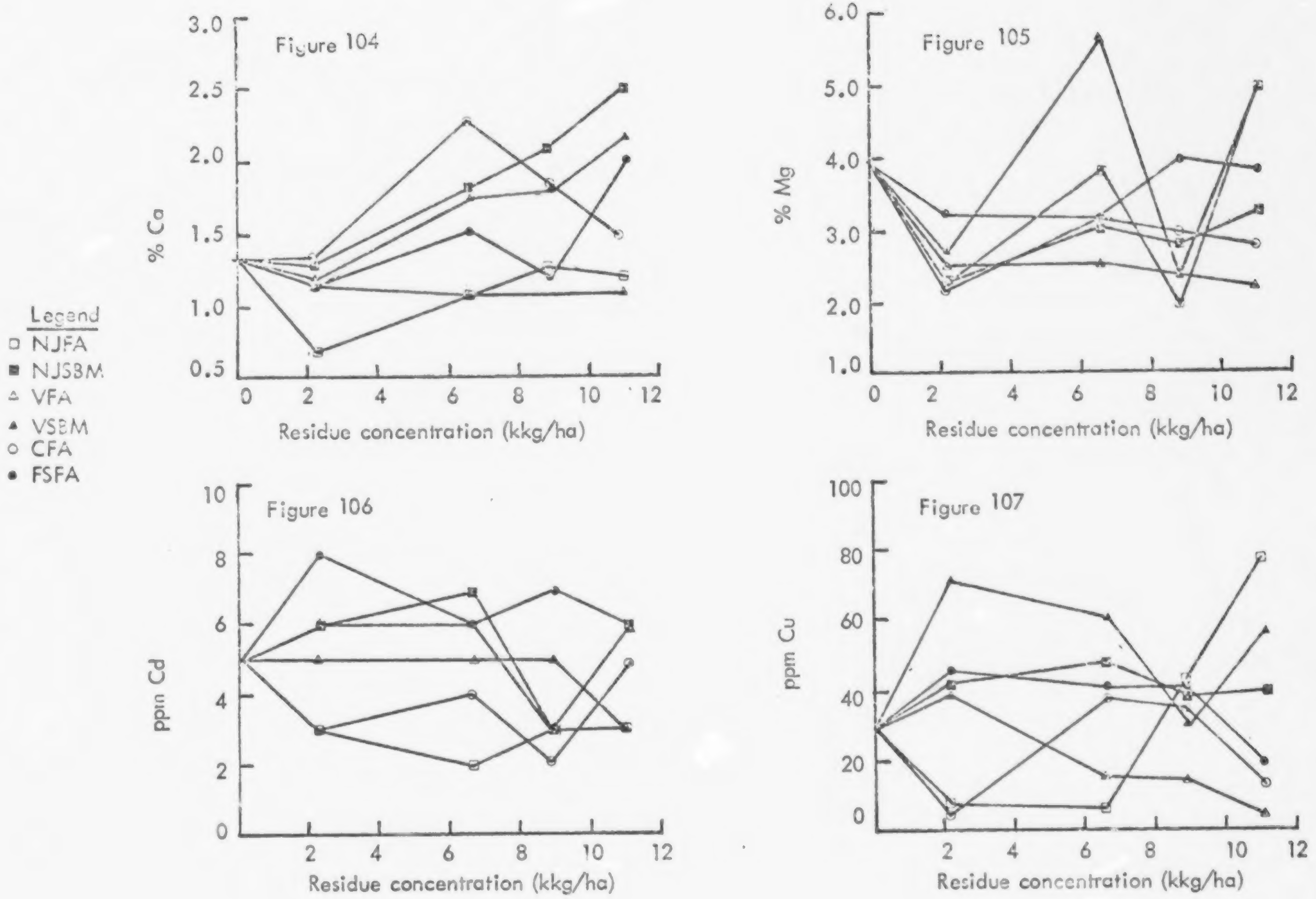
TABLE 104. EXPERIMENT 3: SPINACH TISSUE, CHEMICAL ANALYSIS

Treatment (residual code)	Application Rate (kkg/ha)	Constituents								
		Ca	Mg	SO_4	Cd	Cu	Fe	Mn	Pb	Zn
		(%)			ppm					
Control	0	1.34	4.00	--	5.0	30	311	535	38	270
CFA/T_1	2.2	1.34	2.14	--	3.0	6	164	297	26	180
T_2	6.9	2.34	3.20	--	4.0	38	210	422	37	229
T_3	9.0	--	--	--	2.0	35	126	--	--	--
T_4	11.2	1.49	2.80	—	5.0	14	236	303	34	157
FSFA/T_1	2.2	1.14	3.22	--	8.0	47	446	422	64	191
T_2	6.7	1.54	3.22	--	6.0	42	402	339	57	234
T_3	9.0	1.19	4.06	--	7.0	41	385	465	56	194
T_4	11.2	2.04	3.92	--	6.0	19	394	296	77	214
NJFA/T_1	2.2	0.69	2.36	--	3.0	9	243	324	51	81
T_2	6.7	1.09	3.84	--	2.0	7	192	267	33	74
T_3	9.0	1.29	1.92	--	3.0	43	206	287	37	72
T_4	11.2	1.19	5.06	--	3.0	79	427	220	48	56
NJSBM/T_1	2.2	1.29	2.23	--	6.0	44	299	234	45	66
T_2	6.7	1.84	3.10	--	7.0	49	226	253	39	54
T_3	9.0	2.14	2.86	--	3.0	39	291	190	43	46
T_4	11.2	2.54	3.30	--	6.0	40	417	204	45	50
VFA/T_1	2.2	1.14	2.50	--	5.0	40	310	391	48	119
T_2	6.7	1.09	2.54	--	5.0	18	273	380	39	93
T_3	9.0	1.09	2.40	--	5.0	17	281	370	38	85
T_4	11.2	1.09	2.26	--	3.0	5	162	280	19	98
VSBM/T_1	2.2	1.19	2.64	--	6.0	72	335	455	65	90
T_2	6.7	1.79	5.70	--	6.0	61	390	422	51	145
T_3	9.0	1.84	2.34	--	3.0	30	326	275	34	174
T_4	11.2	2.19	5.10	--	6.0	58	470	349	80	68

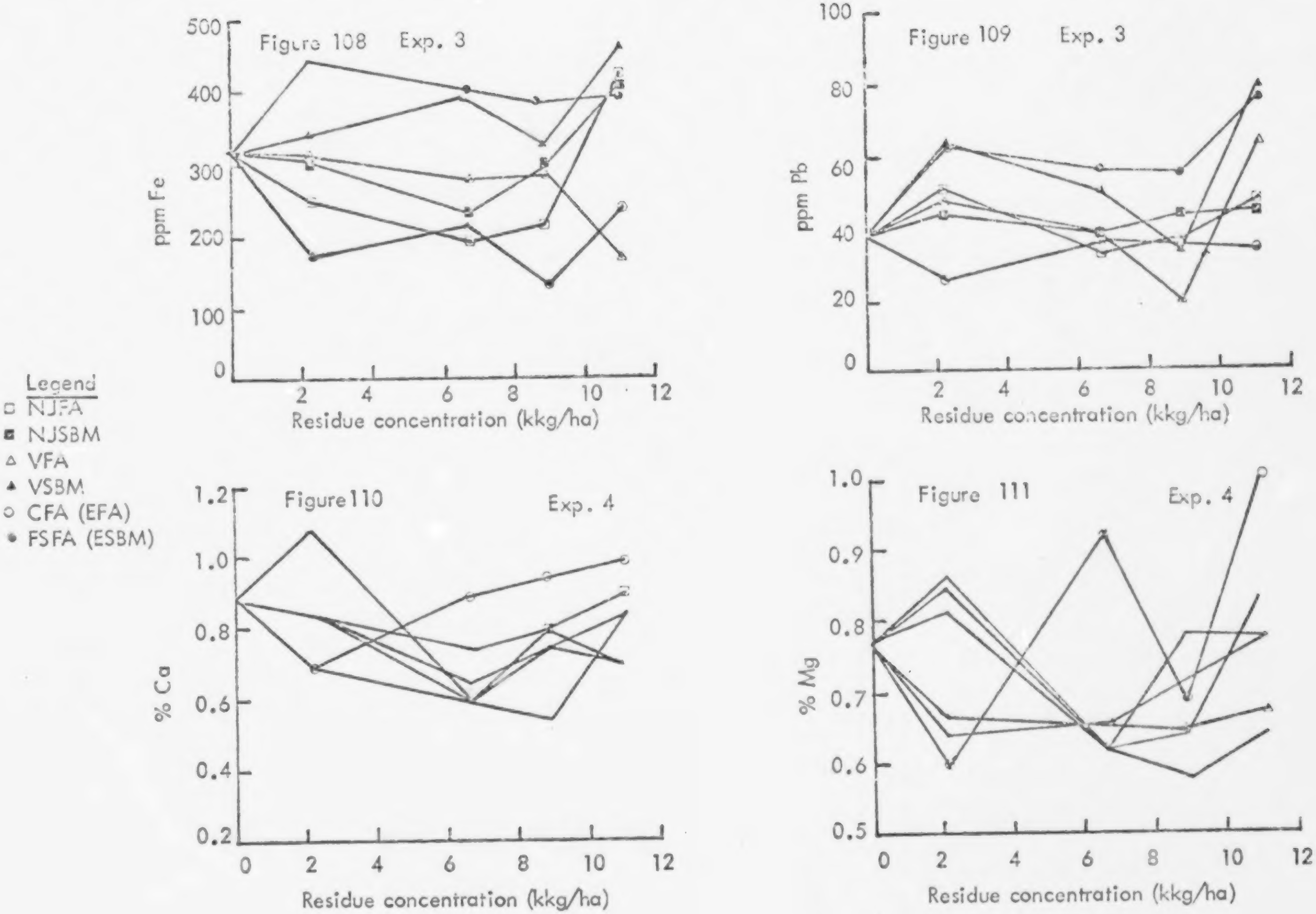
(continued)

TABLE 104 . (Continued)

Treatment (residual code)	Application Rate (kkg/ha)	Constituents						
		K	Na	Ba	Al	Cr	Mo	Ag
		%		ppm				
Control	0	1.23	0.75	40	2,020	5.0	17	5.0
CFA/T_1	2.2	1.29	0.57	60	40	6.0	ND	1.0
T_2	6.7	8.40	0.66	100	510	6.0	ND	1.0
T_3	9.0	--	--	20	200	2.0	ND	3.0
T_4	11.2	1.58	0.39	50	950	6.0	ND	ND
FSFA/T_1	2.2	1.42	0.66	60	2,200	13.0	8	1.0
T_2	6.7	1.36	0.74	60	1,910	11.0	ND	2.0
T_3	9.0	1.31	0.66	50	2,460	8.0	ND	2.0
T_4	11.2	3.13	0.77	60	1,350	10.0	ND	2.0
NJFA/T_1	2.2	2.15	0.56	30	1,030	7.0	ND	2.0
T_2	6.7	1.95	0.55	30	1,160	11.0	ND	ND
T_3	9.0	1.55	0.66	20	1,120	14.0	ND	2.0
T_4	11.2	1.87	0.57	30	650	14.0	ND	2.0
NJBM/T_1	2.2	1.90	0.54	40	1,890	8.0	8	1.0
T_2	6.7	1.73	0.47	30	320	5.0	ND	1.0
T_3	9.0	1.43	0.73	60	1,270	6.0	ND	2.0
T_4	11.2	1.45	0.65	70	1,170	8.0	ND	1.0
VFA/T_1	2.2	1.65	0.60	70	1,020	8.0	8	3.0
T_2	6.7	1.65	0.62	50	3,090	7.0	ND	1.0
T_3	9.0	1.58	0.71	30	2,470	9.0	ND	1.0
T_4	11.2	1.97	0.53	60	1,680	7.0	ND	1.0
VSBM/T_1	2.2	1.36	0.64	50	720	7.0	ND	2.0
T_2	6.7	1.56	1.05	70	1,930	9.0	ND	2.0
T_3	9.0	1.27	0.56	90	390	9.0	ND	3.0
T_4	11.2	1.75	0.73	70	1,110	12.0	ND	3.0



Figures 104 to 107. Experiment 3: Analytical results of calcium, magnesium, cadmium, and copper.



Figures 108 to 111. Experiment 3 and 4: Analytical results of iron, lead, calcium, and magnesium.

hectare or more. The only exceptions were with FSFA/T_2, NJFA and VFA residues which produced plant tissues with lower concentrations than the control soil for the entire range of application rates. Magnesium content was also less in all the vegetation tissue grown in the test soil mixtures containing the equivalent of 2.2 kkg per hectare of residue, and generally was less in the crops grown with higher rates of residue applications. The only plant samples that showed higher concentrations of magnesium than the plant tissues grown in the control soil, were the NJFA/T_4, VSBM/T_2 and T_4 samples. For both cadmium and copper, the chemical content results were variable. Generally, the spinach grown in soil treated with CFA, NJFA, and VFA residues were lower in cadmium concentration than the crop grown in the control soil, and the FSFA, NJSBM, and VSBM treated spinach were higher in cadmium concentration. Likewise, the CFA, NJFA, except NJFA/T_4; and VFA soil admixtures provided plant tissues with less copper concentration than the control crop. Except for FSFA/T_4, VSBM/T_3, and NJSBM/T_3 and T_4, all the other residue-admixed soils grew spinach resulting in highercopper concentration than the control crop.

Experiment 4. Lettuce

Procedure. This experiment was identical to Experiment 3, except that germinated lettuce plants were set on February 1, 1977, and harvested on March 30, 1977, and the six residues used in the experiment were EFA, ESBM, NJFA, NJSBM, VFA, and VSBM.

Results. The results of the analyses of the digested lettuce leaf tissues are shown in Table 105. In all cases, lettuce tissues from the residue-treated soil were significantly lower in minerals such as cadmium, copper, iron, manganese, lead, zinc, potassium, aluminum, chromium, and silver than the control soil residue. In addition, sodium was either equal to or less in the residue-treated crop tissues than in the control crop tissues.

Molybdenum was not detected in any of the lettuce tissue samples. The only other constituents that varied in tissue chemical content were calcium and magnesium. These data are graphically summarized in Figures 110 and 111. Nearly one-half of the crop tissues grown in the residue-treated soil were higher in alkaline metals than the crops grown in the control soil. Except for lettuce tissues grown in EFA/T_3 and T_4, and NJSBM/T_1, the concentrations of calcium were lower in residue-treated lettuce than in the control crop tissues.

Summary

These preliminary screening tests showed that the residues applied at reasonably low rates may be beneficial to the growth of farm crops, particularly in soils with acid or trace element deficiencies. Experiment 2-A indicated that low concentrations of residue increased the pH of the soil, and therefore restricted the uptake of heavy metals by plant tissues and, hence, even reduced their concentration in the plant tissues. The soil pH in Experiments 2,3, and 4 showed a general decrease of metal ion concentrations in the residue-treated crop tissues which indicated that there may have been a trend of increased pH and reduced metal ion plant uptake concentrations. With the various residues used in these experiments, the VFA was more consistent in equalizing or reducing the metal ion

TABLE 105. EXPERIMENT 4: LETTUCE TISSUES, CHEMICAL ANALYSIS

Treatment (residual code)	Application Rate (kkg/ha)	Constituents								
		Ca	Mg	SO_4	Cd	Cu	Fe	Mn	Pb	Zn
		(%)			ppm					
Control	0	0.90	0.78	--	15.0	27.0	376	300	54.0	199
E FA/T_1	2.2	0.70	0.60	--	<1.0	8.0	161	116	10.0	85
T_2	6.7	0.90	0.93	--	1.0	8.0	197	135	16.0	82
T_3	9.0	0.95	0.68	--	1.0	9.0	210	111	18.0	71
T_4	11.2	1.00	1.05	--	1.0	10.0	246	115	22.0	61
ESBM/T_1	2.2	0.85	0.86	--	3.0	17.0	283	87	34.0	91
T_2	6.7	0.65	0.62	--	1.0	4.0	148	72	13.0	55
T_3	9.0	0.75	0.78	--	2.0	9.0	187	115	19.0	64
T_4	11.2	0.70	0.78	--	2.0	11.0	213	78	16.0	60
NJFA/T_1	2.2	0.85	0.87	--	3.0	10.0	214	38	19.0	92
T_2	6.7	0.60	0.62	--	2.0	8.0	150	29	9.0	61
T_3	9.0	0.80	0.58	--	2.0	8.0	133	31	15.0	46
T_4	11.2	0.90	0.64	--	2.0	8.0	282	30	15.0	46
NJSBM/T_1	2.2	1.10	0.82	--	<1.0	9.0	215	53	22.0	57
T_2	6.7	0.60	0.62	--	1.0	8.0	126	40	6.0	61
T_3	9.0	0.55	0.64	--	<1.0	7.0	128	38	4.0	48
T_4	11.2	0.85	0.84	--	1.0	10.0	194	47	29.0	81
VFA/T_1	2.2	0.85	0.67	--	1.0	10.0	147	92	8.0	72
T_2	6.7	0.75	0.65	--	1.0	10.0	177	86	9.0	74
T_3	9.0	0.80	0.65	--	1.0	8.0	134	43	15.0	57
T_4	11.2	0.70	0.67	--	1.0	9.0	180	78	10.0	69
VSBM/T_1	2.2	0.70	0.64	--	3.0	9.0	162	48	15.0	60
T_2	6.7	0.60	0.66	--	3.0	12.0	241	69	22.0	70
T_3	9.0	0.75	0.72	--	2.0	17.0	156	77	14.0	62
T_4	11.2	0.85	0.78	--	3.0	9.0	173	77	16.0	116

(continued)

TABLE 105 (continued)

Treatment (residual code)	Application Rate (kkg/ha)	Constituents K	Na	Ba	Al	Cr	Mo	Ag
		%		ppm				
Control	0	4.98	1.00	50	1,120	18	ND	19.6
EFA/T_1	2.2	1.80	53.08	30	570	2	ND	3.2
T_2	6.7	1.66	0.72	40	330	7	ND	3.9
T_3	9.0	2.20	0.65	30	800	4	ND	3.1
T_4	11.2	1.96	1.03	40	610	7	ND	3.9
ESBM/T_1	2.2	1.36	0.70	60	650	14	ND	1.6
T_2	6.7	1.82	0.71	80	310	7	ND	8.7
T_3	9.0	1.45	0.85	30	230	4	ND	2.4
T_4	11.2	1.62	0.93	30	540	7	ND	3.7
NJFA/T_1	2.2	1.23	0.74	30	550	9	ND	4.7
T_2	6.7	1.31	0.64	30	450	4	ND	4.2
T_3	9.0	1.50	0.61	40	550	8	ND	12.7
T_4	11.2	1.27	0.70	30	190	4	ND	1.7
NJSBM/T_1	2.2	1.27	0.75	30	540	6	ND	2.7
T_2	6.7	0.97	0.57	30	240	<1	ND	2.7
T_3	9.0	1.57	0.68	30	350	2	ND	3.5
T_4	11.2	1.11	0.68	100	270	3	ND	2.9
VFA/T_1	2.2	1.70	0.53	30	560	5	ND	3.5
T_2	6.7	1.41	0.50	20	460	9	ND	2.4
T_3	9.0	1.39	0.65	20	330	6	ND	3.4
T_4	11.2	1.43	0.63	30	700	8	ND	2.7
VSBM/T_1	2.2	1.42	0.70	30	200	3	ND	1.2
T_2	6.7	1.13	0.70	30	810	8	ND	7.2
T_3	9.0	1.11	0.57	30	80	3	ND	0.4
T_4	11.2	1.28	0.53	40	330	6	ND	0.3

concentration in the crops, except for the presence of higher cadmium and silver ion concentrations in the tomato tissues. Experiment 2-B plants grown in soil enriched with the equivalent of 2.2 and 11.2 kkg of residue per hectare indicated that the lower rate of all residue application gave the most consistent results, and that the concentrations of metal ions in the residue-treated crop tissues were generally equal to or lower than those in the control crops.

Excessive concentrations of heavy metals, particularly cadmium, in plants utilized for direct or indirect human consumption are undesirable, and may, in fact, be considered dangerous for human consumption. Soils containing low pH, high metal concentrations, or trace metal deficiencies appear to benefit most from residue applications. A more detailed field scale test program is necessary to determine additional parameters for reclaiming/applying the residues.

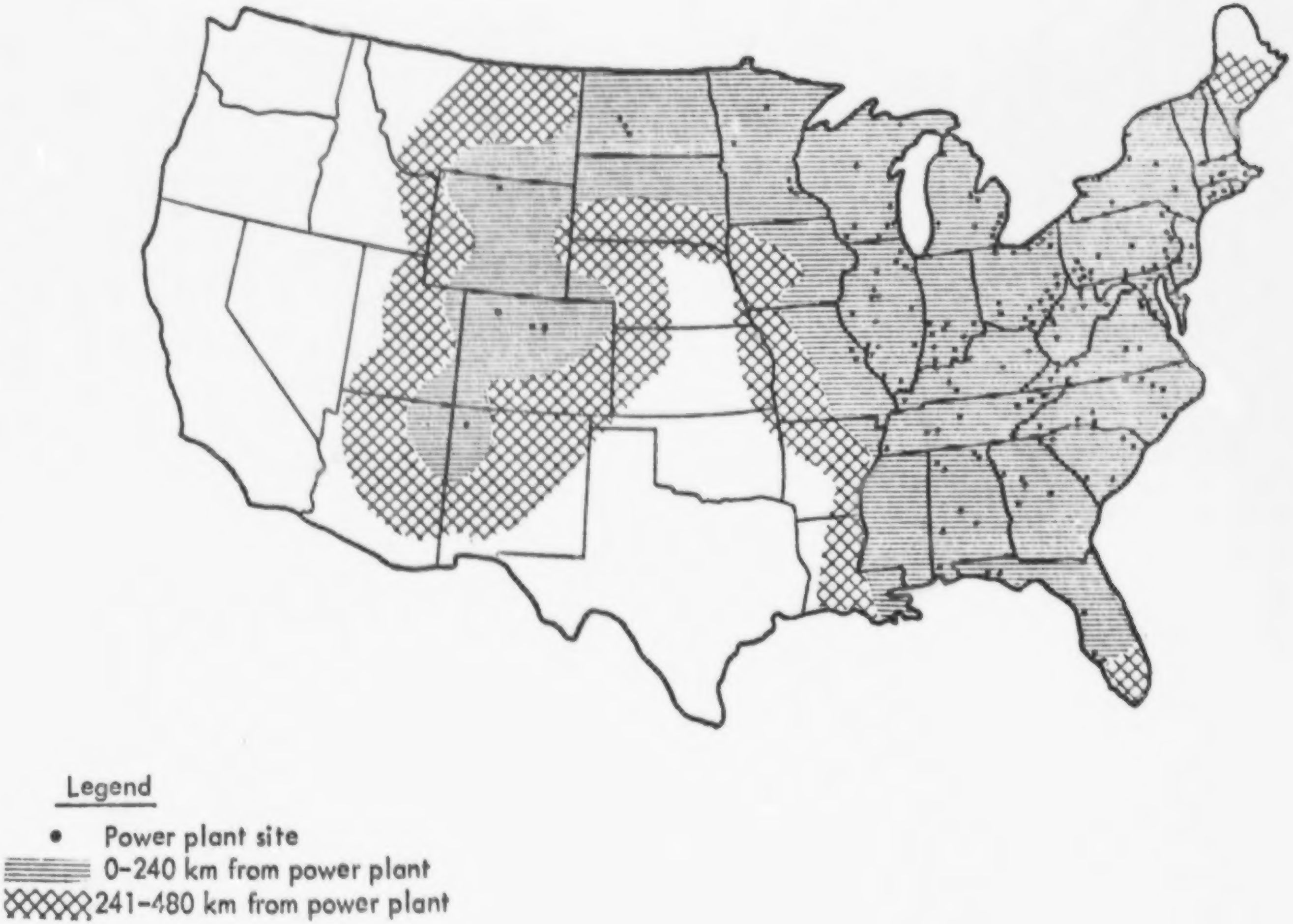
All residue types, soils and climatic crop growth were unique and may require specific evaluation.

Marketing Analysis Methodology

The method of estimating the potential market for fluidized-bed residues in specific applications involved converting data on prices of transport, residues, and conventional materials into the cost-equivalent distance that residues could be economically hauled,and then using data on power plant locations to determine the geographical extent of the potential markey. Figure 112 shows the location of large coal-fired power plants in the United States and adjacent areas within a 240 and 480 km range of the plant. The 240 km distance is shown because after approximately that location, it may be more economical to ship by rail.[54] The 480 km distance is shown only for comparative purposes in order to illustrate that an increase in market area coverage may not be proportional to the increase in travel distance from power plants. Established market patterns that are not easily disrupted, price ration, changes as market penetration increases, and other factors could limit penetration.

The value attributed to residues for any given use should not be considered as the estimate of its market price. First, the residues have more than one possible use. For each use there will be a certain relationship between the demand for the residues and their delivered price. The aggregate demand relationship for the residues will be the sum of the demand functions for the different uses. Second, the willingness of sources to supply residues at various prices would also influence their market price. In other words,market price is determined by the interaction of both demand and supply conditions, not just by use value.

The most direct method of estimating the value of a substitute input to a production process is to impute its value from the cost of the inputs replaced by the new input, holding the output constant. Suppose, for example, that 1,000 kg of peanuts could be grown on a given plot using either 100 kg of ordinary lime (the conventional input) or by using 200 kg of spent bed material from a fluidized-bed power plant (the new input). Suppose further that the delivered price for ordinary lime is $2 per kg and that there is no established market(and thus no price) for the residues. In this situation, the imputed value of


Legend
● Power plant site
▤ 0-240 km from power plant
▦ 241-480 km from power plant

Source: 54.

Figure 112 . Distance to large U. S. coal-fired power plants.

the residues would be $1 per kg (delivered) based on 200 kg ($200) residues equalling 100 kg ($200) of lime as a soil conditioner. This means that if a market for residues were established, a rational producer would switch from lime to residues if their delivered price was less than $1 per kg.

Sometimes it may not be possible to impute the value of the residues in a given application from the cost of the displaced inputs. This would be the case if it cannot be readily determined how much of which inputs can be replaced by a unit of the new input at the given output level. In such a case, it may be possible to impute the value of the residues from their impact on output. Several examples are given below to illustrate the method and its pitfalls.

If the experimental data available indicated that 200 kg of residues yielded 1,000 kg of peanuts, and that the price of peanuts is $0.50 per kg, we could not conclude that the value of the residues is $2.50 per kg (1,000 x 0.50/200). It is likely that, even without any residues, some peanuts would have been produced. Suppose, then, that without any inputs, 500 kg of peanuts would have been produced. Again, this does not imply that the value of the residues is $1.25 per kg (500 x 0.50/200) since other inputs might be able to achieve the same result (in this case, 100 kg of lime). Taking the example a bit further, suppose that 300 kg of residues would yield 1,400 kg of peanuts. The value of the extra output would be $200, and the residues would still be replacing $200 worth of lime. Could we conclude from this that the proper input value for the residues is $1.33 per kg? Perhaps, but only if several restrictive conditions were shown (or assumed) to hold. The imputed value would be wrong, for instance, if a lower lime application rate could achieve the same yield. It would also be wrong if a third input (a source of sulfur, for example) could be used in conjunction with lime to achieve the same yield. This would be the case where the residues serve a function not served by the input being replaced. The problem with imputations based on output changes is that they may misrepresent the situation. The appropriate question with respect to any imputed value for an input is, whether or not a rational producer would adopt that input if its price were less than the imputed value. If not, then the imputed value would be invalid.

The delivered cost of standard quality residues is a prime consideration to the potential user. Most of the ash currently being reused is removed by a broker (or the ultimate user) at no cost to the utility. In that situation, the price (or cost) to the user will represent charges for (1) pick-up, (2) transport, (3) quality standardization, and (4) profit to the broker. For purposes of analysis, the broker profit will be neglected, although a fixed percentage could be included in the calculation. For many reuse applications, it is important that the chemical and physical characteristics of the residues are standarized within reasonable limits. Variations in residue parameters may limit its usability. Obviously, for some applications, physical and chemical variations would be significant; for others, they may make little difference. For certain uses it has been estimated that the delivered price of fly ash assuming uniform quality could be as high as $10 to $14 per kkg.

Shipping costs will affect the delivered prices for residues and virgin raw materials. With widespread adoption of fluidized-bed processes, most areas of the nation (with the possible exception of the West) will have ready, close-by access to residues. In many cases, access to residues may even be better than for alternative conventional raw materials. Approximate truck transport costs in 1977 were \$0.04 per kkg/km (with 18 to 27 kkg per truck). For short hauls, an extra charge of \$1.00 for loading and the same charge for unloading has been assumed. As stated previously, the maximum efficient range for truck transport is estimated to be about 240 km (depending on road conditions), since at that distance the driver can get to his destination, unload, and return on the same day, while avoiding overtime and other costs for a layover.[54] For rail transport, a car-lot is about 50-54 kkg and transport cost about \$0.02 per kkg/km, plus an additional fee for shaking the car to complete unloading. It should be noted that rail freight rates discriminate about 20 percent against secondary materials (such as fly ash) in comparison to primary materials.

Although current practice provides zero-cost pickup of residues from some power plants, it may be reasonable to assume that utilities must generally pay to have them removed. The value of the fly ash to them is not zero, but rather is less than zero by the unit they have to pay to dispose of the residues. The cost of land disposal has been, and is projected to continue increasing in response to: (1) the impact of general inflation on transport and handling costs, (2) increasing scarcity of acceptable, close-by landfill sites, and (3) increasing strict environmental regulations on waste disposal. Disposal cost will vary from place to place, but can genrally range from \$3 to \$6 per kkg. Costs may be even higher if special treatment is necessary prior to disposal. For example, chemical fixation followed by landfilling is one method of treating the residues from limestone flue-gas desulfurization systems. The experience of several firms with that process is shown on Table 106.

Thus, certain applications not judged economically feasible if the residue cost was zero at the power plant may be acceptable if the power plant paid for removal of the residues. Because of the difficulties in estimating (1) what the utility would be willing to pay for residue removal, and (2) the cost of insuring adequate residue quality, in the remainder of the analysis, it will be assumed that these two factors balance one another and that the residues are available at a zero cost.

Economic Analysis of Specific Applications

Concrete

Substantial research (discussed above) exists showing that adding fly ash to concrete can improve the characteristics of the concrete. The fly ash can be used to replace aggregate and, because it is also a pozzolan, a portion of the portland cement. Based on preliminary research results, concrete mixtures with approximately 5 percent residue content display improved strength characteristics. Table 107 compares the composition of the optimal concrete mix (as determined in the testing program) containing residues to that of a standard concrete mix (used as a control for the tests). The table also estimates the cost savings from using residues as a partial substitute for aggregate and portland cement which would result if residues were available at a free delivered price. This saving would be

TABLE 106. SLUDGE FIXATION COSTING ESTIMATES

All values are condition and site dependent

Source	Cost ($/kkg, 50% solids)	Remarks
Commonwealth Edison Company, Will County Station	6.50	On-site disposal--vendor quote
	9.41	Current estimate[a]
	5.78	Best experience[a]
	11.00	Worst experience[a]
	5.50	Target[a]
Duquesne Light Company, Phillips Station	7.98	Total disposal
International Utilities Conversion Systems, Inc.	1.65-2.75	On-site disposal
Chemfix	5.50	On-site disposal
Dravo Corporation	1.65-3.30	Total cost to customer; includes pumping to 10 mi

[a] Company Operation - on-site disposal; excludes capital costs.

$0.50 per kkg of concrete. Since 53 kg of residues would be used in one kkg of concrete, the imputed value of the residues would be $0.50/53 kg or about $0.01 per kg of residue. This implies that a concrete producer would (all other things equal) use the residues if their delivered price were about $0.01 per kg or less. To the extent that the improved characteristics imparted by the residues to the concrete results in a higher market price for the concrete, the producer may be willing to pay in excess of $0.01 per kg delivered for the residues. Assuming an imputed value of $0.01 per kg, a rail freight rate of $0.02 per kkg-km, and a zero f.o.b. price for the residues at the power plant site, residues could be rail-hauled a distance up to 472 km and remain competitive. By truck, they could be economically transported about one-half that distance.

TABLE 107 . RESIDUE VALUE FOR USE IN CONCRETE

Item	Composition		Value($/kkg)[a]		Cost Reduction ($/kkg)
	Control	Residue Added	Control	Residue Added	
Concrete component					
Fly ash	0	5.3	0	b	0
Aggregate	71.5	64.7	3.55	3.21	0.34
Portland cement	15.2	14.9	8.02	7.86	0.16
Water	13.3	15.1	0	0	0
Total	100	100	11.57	11.07	0.50

[a] Based on a delivered cost (in Los Angeles) for portland cement of $52.78/kkg and for aggregate of $4.96/kkg.

[b] Value of residue to be imputed from savings from its use ($11.57 - $11.07 = $0.50/kkg)

Asphalt

Coal ash has been used successfully as a replacement for aggregate in asphalt for some time. For example, the West Virginia Department of Highways has found that an asphalt surface coating with a thickness of 5 to 7.5 cm made from dry bottom-ash and emulsified asphalt works satisfactorily and its cost is about half that of conventional asphalt. The low cost results from two factors. First, there is a large, readily available supply of coal ash located conveniently throughout the state. Second, the technology required is simple and the same as needed with conventional asphalt. Ash is loaded into a portable continuous pugmill, frequently located at the power plant site, and mixed with a metered amount of emulsified asphalt. Then it is either loaded directly on trucks or stockpiled for future use. The well-graded ash usually requires no additional blending. Using emulsified asphalt makes heating and drying unnecessary, thus eliminating the need for relatively costly hot bins or dryers.

Other examples of successful use of coal-ash residues in asphalt could be cited; but, even though the technology appears simple and sound, use in this application has remained quite limited (approximately 180,000 kkg of residues in 1972)[131] There does appear to be a substantial potential market, however. In comparison to a delivered (Los Angeles) price of aggregate of $4.96 per kkg, conventional coal-combustion residues could be transported approximately 250 km by rail (at $0.02/kkg-km) or 125 km by truck (at $0.04/kkg-km) and be competitive.

Little work has been done on limestone or dolomite modified residues. Wet-collected residues from flue gas desulfurization systems appear to have some promise in asphalt applications. However, if substantial dewatering or drying is required prior to use, the cost may be prohibitive. Fluidized-bed residues are collected dry, and appear to have a higher potential. Preliminary tests were conducted to determine the technical feasibility of using fluidized-bed residues in a mixture with emulsified asphalt. The results indicated that up to 92 percent of the aggregate could be replaced. Table shows the approximate savings which could be realized assuming a free delivered price for the residues, and 92 percent replacement. For any given transport distance (or delivered price for residues) the net savings or costs per unit of asphalt can be easily calculated.

TABLE 108. IMPUTED VALUE OF RESIDUES IN ASPHALT APPLICATIONS

Item	Composition (%)		Value ($kkg)[a]		Cost Reduction ($/kkg)
	Control	Residue Added	Control	Residue Added	
Asphalt Component					
Emulsified asphalt	8	8	94.53	94.53	0
Aggregate	92	0	4.96	0	4.96
Fly ash	0	92	0	b	0
Total	100	100	99.49	94.53	4.96

[a] Based on a delivered cost (in Los Angeles) for asphalt of $93.53/kkg and for aggregate of $4.96.

[b] Value of residue to be imputed from savings from its use.

Agriculture

Fluidized-bed residues can improve crop growth and yield by (1) altering pH (the residues are quite alkaline), (2) improving soil structure, (3) providing essential micronutrients (Zn, Cu, Fe, Mn, B, Cl, Al), (4) providing sulfur, and (5) serving as a source for macronutrients (O, C, H, N, P, K, Mg, Ca). Thus, the residues can serve many functions as an agricultural input. The purpose of this analysis is to estimate the value of the residues for agricultural applications. Because both the residues and many conventional agricultural inputs serve multiple functions, it is sometimes difficult to identify the inputs which, in a given application, could be replaced by fluidized-bed residues. Therefore, some of the analysis below will be based on the value of yield changes.

Research currently being conducted at the Virginia Polytechnic Institute and State University[84] has indicated that fluidized-bed residues can be used as a source of calcium for large-seeded peanuts, at least partially replacing application of calcium carbonate. The impact of providing a calcium source and a comparison between equal applications (980 kg/ha) of residue and calcium carbonate on yield were beneficial. On the average, both had a positive impact on yield, with the calcium carbonate increasing yield by 17 percent and the residue increasing it by 11 percent. However, at the given application rate, it is implied that the delivered price of residues would have to be significantly less than that for calcium carbonate to make up the lower yield obtained. For example, the delivered price of calcium carbonate in Los Angeles, California, is about $13.60 per kkg. Applying 980 kg to one hectare would cost $13.33 for the material and result in (on the average) an extra $84 of peanut production. Because the residues, as a source of calcium, are not as good as calcium carbonate on an equal weight basis, the farmer would have to be paid $72.11/kkg to accept residues to make it economical for him to do so. Since this payment is unrealistic, use of residues in this application cannot be predicted on the basis of field test results.

However, one factor, transporting costs, suggests that such application could be economically feasible. Although the calcium content of available calcium carbonate is about 40 percent, in comparison to the residues' approximate 10 percent, a higher residue application rate may result in matching yields achieved with calcium carbonate. For example, suppose 3,860 kg of residues per hectare could achieve the same yield as 980 kg of calcium carbonate per hectare (this would equalize calcium content). In this situation, the imputed value would be $3.40 per kkg and, assuming the residues had a zero f.o.b. price at the power plant, the economically feasible transport distance would be 170 km by rail and 85 km by truck. This is, of course, a hypothetical result and more experimental work needs to be completed before the economic feasibility of this application can be determined.

Test Plot D in Table 109 shows an improvement in yield for the spent bed material versus the calcium carbonate. As discussed above, the residues may fulfill several functions in plant growth. Apparently in Plot D, a growth requirement is being met by the residues which calcium carbonate does not meet. The value (relative to calcium carbonate) in this application is $250 for increased yield and $13 saved by replacing calcium carbonate, for a total value of $263 per 980 kg. This represents an imputed value for the spent-bed material of $268 per kkg. However, there would likely be other inputs capable of filling the same need, and the proper comparison would be without that input. There is some evidence that in certain types of soil, the fluidized-bed residues will achieve higher yields than will ordinary limestone, even at equal application rates. The VPI study identified "Woodstock loamy fine sand" as possibly being such a soil type.

TABLE 109. FLUIDIZED-BED RESIDUES AS A SUBSTITUTE FOR CALCIUM CARBONATE IN PEANUT GROWING

Material Applied	Application Rate (kg/ha)	Test Plot Yield ($/ha) A	B	C	D	E	Avg
Control	0	1190	1097	1097	1225	1862	1457
Calcium carbonate	980	1420	1337	2109	1489	1894	1699
Spent-bed material	980	1317	1151	2040	1739	1830	1615

Source: 84.

Fluidized-bed ash and spent-bed material are both quite alkaline and, hence, can be used to raise soil pH. In that function, it is a substitute for slaked lime ($Ca(OH)_2$). The delivered price of slaked lime in Los Angeles is approximately $65 per kkg. The amount of NJFA necessary to cause the same pH adjustment as the slaked lime has been estimated to be 13.5 kg; for NJSBM, the equivalent is 5.5 kg. This corresponds to an imputed value for NJFA of $4.80 per kkg and for NJSBM of $11.80 per kkg. Again, assuming a zero f.o.b. price at the power plant, the NJFA residues could be economically transported 240 km, and the NJSBM residues 590 km by rail. It should be stressed, however, that these calculations assume that the only function provided by either the residues or the slaked lime is pH adjustment. Since this is not the case, it would be necessary to know the yield response for different types of soils and plants in order to draw firm conclusions on the economic feasibility of this application. Each conclusion would be specific for a given type of crop and soil condition.

The market for pH adjustment materials is quite large. On an average, 675-900 kg/ha/year of limestone is needed to maintain an optimal soil pH in areas where large quantities of nitrogen fertilizers are used. For several reasons, one of which is the expense of limestone, less limestone is used than is necessary for optimal yields. It has been estimated that in the United States, about 80-90 million kkg of limestone could be used annually to advantage.[12] In those areas where the delivered price of residues is significantly less than for limestone, on an equivalent basis it can be expected that farmers would more nearly approach the optimal level of application. The potential market for the residues is therefore substantially greater than our projected generated rate of 2 to 12 million kkg per year for 1995. As discussed previously, however, there are also substantial impediments to large-scale utilization for this purpose, such as transportation costs and the need for farmer education and acceptance.

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APPENDIX A

LABORATORY ANALYTICAL METHODS

Chemical analyses were performed on leachate from the laboratory-scale columns, the pilot scale columns, and test cells. Environmental Protection Agency methods (Manual of Methods for Chemical Analysis of Water and Wastes, EPA 625/6-74-003) were used for all analyses. The analyses performed, the methods used, and references for the methods are shown in Tables A-1 through A-3.

To insure the validity of the test results, EPA-approved quality control procedures were instituted. The program involved co-analysis of a series of standards, duplicate unknowns, and spiked unknowns. One duplicate was run for every four samples; where there were fewer than four samples, all were duplicated. Spikes were run on one of every eight samples; for fewer than eight samples, at least one spike was run. Standards were scattered throughout the runs to maintain instrument calibration. All reagents were checked for stability on a rotating basis which covered each reagent at least twice yearly.

TABLE A-1. SOIL PREPARATORY METHODS

Purpose	Method	Reference[a] (page number)
Total Residue Characterization	Hydrofluoric and perchloric acid digestion	1019
Soluble Fraction Analyses	Water extraction	935
	Acid extraction (1.0 N nitric acid)	935[b]
	Base extraction (1.0 N sodium hydroxide)	935[c]
Cation Exchange Capacity	Sodium saturation	899
Tomato Plant Analyses	Wet digestion	11[d]

[a] American Society of Agronomy. Methods of Soil Analysis, Part 2. Madison, Wisconsin; 1965; except as noted.

[b] Same as water extraction, except nitric acid solution was substituted for distilled water.

[c] Same as water extraction, except sodium hydroxide solution was substituted for distilled water.

[d] Sub-committee of NC-118. Sampling and Analysis of Soils, Plants, Waste Waters, and Sludge. Research Publication 170, Agricultural Experiment Station, Kansas State University, Manhattan, Kansas.

TABLE A-2, SOIL TESTS

Test	Method	Serial Designation	Page Number
Moisture Content	Gravimetric, oven-drying	D2216	276
Particle Size Analysis	Hydrometer	D422	70
Permeability	Constant Head	D2434	294
Specific Gravity	Pycnometer	D854	157

Source: 192.

TABLE A-3. ANALYTICAL METHODS

Parameter	Performed on RC[a]	LCL[b]	PCL[c]	PD[d]	Method	Reference[e] (page number)
Metals						
Aluminum	X				Colorimetric (Eriochrome cyanide R)	92
Arsenic		X			Colorimetric (Silver diethyldithiocarbamate	9
Beryllium	X				Atomic Absorption	99
Cadmium	X	X			Atomic Absorption	101
Calcium	X	X			Flame Emission	103
Chromium	X				Atomic Absorption	105
Copper	X				Atomic Absorption	108
Iron	X	X	X	X	Atomic Absorption	110
Lead	X	X	X		Atomic Absorption	112
Magnesium	X	X		X	Atomic Absorption	114
Manganese	X	X	X	X	Atomic Absorption	116
Mercury	X	X	X		Flameless Atomic Absorption	118
Nickel	X	X	X		Atomic Absorption	141
Potasium	X	X			Flame Emission	143
Silver	X	X	X		Atomic Absorption	146
Sodium	X	X			Flame Emission	147
Zinc	X	X	X	X	Atomic Absorption	155
Physical						
Total Dissolved Solids	X		X		Gravimetric	267
Specific Conductance			X		Electrometric (platinum electrode)	275
Inorganic						
Boron	X	X			Colorimetric (Curcumin)	13
Chloride	X	X	X		Titrimetric (Mercuric nitrate)	29
Nitrate	X	X			Colorimetric (Brucine)	197
pH	X	X	X	X[f]	Electrometric	239
Phosphate	X				Colorimetric (Ascorbic Acid)	481[g]
Sulfate	X	X	X	X	Turbidimetric	277
Organic						
BOD	X	X			Manometric	1558[h]
COD					Dichromate reflux	
	X		X		Low Levels	21
			X		High Levels for Saline Samples	25

(continued)

TABLE A-3 (continued)

[a] RC - Residue characterization.

[b] LCL - Lab column leachate.

[c] PCL - Pilot column leachate.

[d] PD - Plant digested sample.

[e] U. S. Environmental Protection Agency. Manual of Methods for Chemical Analysis of of Water and Wastes. EPA-625/6-74-003. Washington, D. C. Office of Technology Transfer, US EPA, 1974.

[f] Analyzed on 1:1 plant/distilled water mixture.

[g] American Public Health Association, Standard Methods, 14th ed., Washington, D. C., 1976.

[h] American Society of Agronomy. Methods of Soil Analysis, Part 2. Madison, Wisconsin, 1965.

APPENDIX B
SAMPLE DATA SHEET

SURVEY OF PILOT PLANTS USING FLUIDIZED BEDS FOR THE COMBUSTION OF COAL AND THE GASIFICATION OF HIGH-SULFUR FUEL OILS

We are conducting special studies for the U.S. EPA (Contract No. 68-03-2347; Project Officer, Richard Chapman: 1346 Willow Road, Menlo Park, California 94025) on the residues from the fluidized bed combustion of coal and the gasification of high-sulfur fuel oils. The purpose of this questionnaire is to provide us with basic design information on the pilot plants covered by the study to aid in our assessment of residue disposal impacts. Please complete and return to:

Ralph Stone and Company, Inc.
10954 Santa Monica Boulevard
Los Angeles, California 90025 USA
Phone: (213) 478-1501 and 879-1115

1. General Pilot Plant Characteristics
   a. Name of plant: ____________________
   b. Address: ____________________
   ____
   ____
   c. Designer: ____________________
   Address: ____________________
   ____
   ____
   d. Operating organization: ____________________
2. Construction Information
   a. General contractor: ____________________
   b. Construction commencement date: ____________________
   c. Construction completion date: ____________________
   d. Start-up date: ____________________
   e. Total capital cost: ____________________
3. General Information
   a. Number of employees required to operate pilot plant: ____________________
   b. Number of operating days in 1975: ____________________
   c. Number of days shut down for maintenance, process modification, etc.: __________
   d. Estimated annual operating cost: ____________________

4. Operating Information. Please give design estimates rather than actual operating values. Answer in listed units of measure, if possible; if other units are used, please specify them.

a. Bed volume (cu m): ____________________

b. Quantity of bed material (kg): ____________________

c. Average bed material feed rate (kg/min): ____________________

d. Average particle size of bed material (cm): ____________________

e. Mode of operation

(1) Number of stages: ____________________

(2) ( ) Batch; ( ) continuous (check one)

(3) ( ) Once through; ( ) regenerated (check one)

f. Coal or oil feed rate (kg/hr): ____________________

g. Air requirements (scfm): ____________________

h. Fuel hydrogen requirements (scfm): ____________________

i. Combustion efficiency: ____________________

j. Power output (kwhr): ____________________

k. Heat released (Btu/hr): ____________________

l. Please describe number and types of flue gas control equipment (cyclones, scrubbers, etc.).

____

____

____

____

m. Quantities and types of wastes produced.

solid:

fly ash: ____________________

spent bed material: ____________________

liquid:

type: ____________________; quantity: ____________________

type: ____________________; quantity: ____________________

4. Operating Information (cont.)

n. Describe handling and storage facilities used for the different kinds of wastes.

5. Please provide a copy of the results of any analyses which have been conducted on the spent bed material and fly ash and copies of recent progress or other reports.

Use the space below or an additional page for additional comments.

Thank you for your generous cooperation.

APPENDIX C

CHARACTERIZATION OF SIMILAR RESIDUES

Coal Ash

Coal ash is primarily an iron-aluminum-silicate material which contains lime, magnesia, sulfur trioxide, sodium and potassium oxides, and carbon, as well as traces of heavy metals. Although the specific composition of a coal ash is mainly dictated by the geology of the coal deposit and the operating parameters of the boiler unit, many common minerals are present in United States coal. A breakdown of these minerals is given in Table C-1. Table C-2 tabulates a more detailed compilation of typical coal ash chemical constituents. The soluble constituents of coal ash from distilled water are summarized in Table C-3.

During combustion, the inorganic minerals in the coal were subjected to furnace temperatures between 1400° C and 1700° C. At these temperatures, the minerals can react to form mullite, quartz, hematite, and calcium sulfate. The distribution range for these mineral phases is compiled in Table C-4.

Fly ash generally occurred as fine spherical particulates ranging in diameter from 0.5 to 100 , and had an average diameter of 7 . The color of fly ash can range from light tan to gray to black, depending on the iron and carbon content. The pH of fly ash can vary from 6.5 to 11.5 and can average about 11. A summary of the typical physical properties of fly ash is presented in Table C-5. Figure C-1 diagrams the concentration range of the major constituents in United States fly ash.

The residue recovered from the bottom of a coal-fired boiler unit occurs as either bottom ash or slag. These residues are typically composed of gray to black, porous, angular particles. Depending on the type of boiler process used, some particles can have a glassy appearance.

The fly ash modified by limestone or dolomite injection into boilers has significantly different composition from normal fly ash. The ash compositions generated by the combustion of bituminous coal and lignite coal are compared with the ashes obtained in the limestone and dolomite injection processes in Table 54.

Municipal Incinerator Residue

During incineration, furnace temperatures were between 980° and 1100° C, with flame temperatures at approximately 1400° C. This process resulted in the reduction of the incinerated refuse to 25 to 35 percent of its original weight and to less than 10 percent of its volume. The resultant residue after quenching was a wet, complex mixture of metal, glass, slag, charred and burned paper, and ash. It was the ash that was important here because its chemical composition was very similar to that of fly ash from coal burning boilers. In comparison, the fly ash was predominantly 200 microns in size, and consisted of wood and paper ash, aluminum foil, carbon particles, metal pins and wire, glass, sand,

TABLE C-1. COMMON MINERALS IN U.S. COALS

Pyrite, marcasite - FeS_2
Chalcopyrite - $CuFeS_2$
Arsenopyrite - $(FeS_2 \cdot FeAs_2)$
Stibnite - Sb_2S_3
Gypsum - $CaSO_4 \cdot 2H_2O$
Calcite - $CaCO_3$
Quartz - SiO_2
Siderite - $FeCO_3$
Kaolinite - $Al_2Si_2O_5(OH)_4$(7)
Dolomite - $CaMg(CO_3)_2$
Apatite - $Ca_5(F, Cl, OH)(PO_4)_3$
Mica - $KAl_2(Si, Al)_3O_{10}(OH)_2$

TABLE C-2. CHEMICAL CONSTITUENTS OF COAL ASH

Constituents	Range (%)	Average (%)
Silica (SiO_2)	20 - 60	48
Alumina (Al_2O_3)	10 - 35	26
Ferric oxide (Fe_2O_3)	5 - 35	15
Calcium oxide (CaO)	1 - 20	5
Magnesium oxide (MgO)	0.25 - 4	2
Titanium dioxide (TiO_2)	0.5 - 2.5	1
Potassium oxide[a] (K_2O)	1.0 - 4.0	2
Sodium oxide[a] (Na_2O)	0.4 - 1.5	1
Sulfur trioxide (SO_3)	0.1 - 12	2
Carbon (C)	0.1 - 20	4
Boron (B)	0.01 - 0.6	Trace
Phosphorus (P)	0.01 - 0.3	Trace
Manganese (Mn)	0.01 - 0.3	Trace
Molybdenum (Mo)	0.01 - 0.1	Trace
Zinc (Zn)	0.01 - 0.2	Trace
Copper (Cu)	0.01 - 0.1	Trace
Mercury (Hg)	0.0 - 0.02	Trace
Uranium (U)	0.0 - 0.1	Trace

[a] Alkalies

Source: 88.

TABLE C-3. CHEMICAL CONSTITUENTS OF COAL ASH

Soluble Ions	Range (for 1-1.7% dry solids)
Ca^{++}	200 - 850 ppm
Mg^{++}	185 - 400 ppm
$SO_4^{=}$	200 - 250 ppm
K^+	Trace
Na^+	Trace
$PO_4^{\equiv}$	0 - 5 ppm
BO_3^-	0 - 10 ppm

Source: 128.

TABLE C-4. MINERAL PHASES FOUND IN COAL ASH

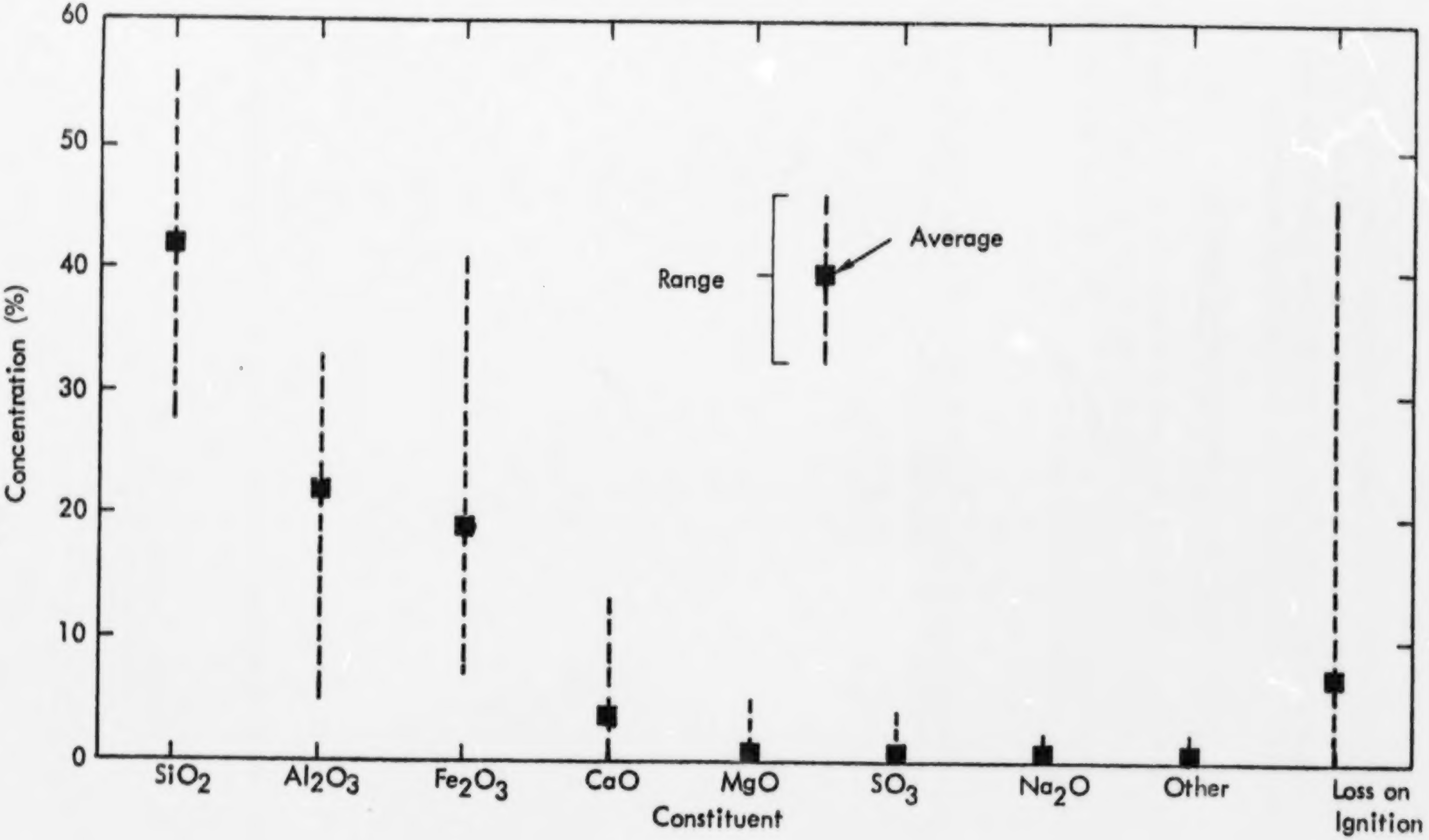
Phase	Percent
Quartz	0-4
Mullite	0-16
Magnetite	0-30
Hematite	1-8
Glass	50-90

Source: 126.

TABLE C-5. PHYSICAL PROPERTIES OF FLY ASH FROM PULVERIZED COAL FIRED PLANTS

Constituents	Unit	Range
Range of particle size	microns	0.5-100
Average percent passing No. 325 sieve (44μ)	percent	60-90
Bulk density (compacted)	kg/cu m	1,100-1,300
Specific gravity		2.1-2.6
Specific area/gram	cu cm/g	3,300-6,400

Source: 69.



Source: 34.

Figure C-1. Concentration range and average of U. S. fly ash constituents.

and iron scale. A general analysis of the inorganic components found in fly ash is presented in Table C-6. A comprehensive elemental analyses for four different municipal incinerator fly ashes is presented in Table C-7. It has also been reported that small amounts of cadmium, lead, and mercury have been found in fly ash samples.

Sludge From Lime-Limestone Scrubbing Processes

In Table C-8, chemical analyses of nine sludges collected from nine different lime-limestone scrubbing processes are presented. The nine different sources or conditions under which these sludges were produced are listed in Table C-9. The results of an X-ray analysis performed on these sludges are listed in Table C-10.

TABLE C-6. OXIDE ANALYSES OF INCINERATOR FLY ASH FROM TYPICAL REFUSE

Component	Total Oxide Content (%)
SiO_2	53.0
Al_2O_3	8.2
Fe_2O_3	2.6
CaO	14.8
MgO	9.3
Na_2O	4.3
K_2O	3.5
TiO_2	4.2
SO_3	0.1
P_2O_5	1.5
ZnO	0.4
BaO	0.1
	102.0

Source: 41.

TABLE C-7. ELEMENTAL HEAD SAMPLE ANALYSES OF MUNICIPAL INCINERATOR FLY ASHES (% by weight)

Sample	Ag	Al	Ba	C	Ca	Cu	Cr	Fe	K	Mg	Mn	Na
F-1	0.02	11.63	0.11	5.16	5.23	0.08	0.11	3.22	1.66	0.99	0.40	1.93
F-2	0.01	11.03	0.09	0.68	6.09	0.13	0.06	3.21	0.76	0.94	0.11	2.28
F-3	0.07	13.31	0.23	0.42	4.25	0.06	0.05	2.05	1.12	0.99	0.07	1.55
F-4	0.01	11.51	0.11	11.18	4.16	0.05	0.06	2.11	1.92	0.92	0.15	1.09

Sample	Ni	P	Pb	S	Si	Sn	Ti	Zn	Au
F-1	0.04	0.76	0.50	0.47	17.98	0.18	1.54	0.74	0.01
F-2	0.03	0.63	0.40	0.40	22.88	0.14	1.13	0.60	0.01
F-3	0.03	0.60	0.26	0.51	20.57	0.13	1.88	1.50	0.01
F-4	0.02	0.63	0.38	0.32	18.03	0.18	1.41	0.63	0.01

Source: 33.

TABLE C-8. WET CHEMICAL ANALYSIS OF SLUDGE STANDARDS[a]

	STD I	STD II	STD III	STD IV	STD V	STD VI	STD VIA	STD VII	STD VIII	STD IX
SiO_2	46.7	1.5	30.7	0.79	19.4	1.1	27.7	4.6	1.2	2.0
Al_2O_3	23.2	0.32	6.6	0.05	6.8	0.01	14.7	2.3	0.48	0.45
Fe_2O_3	13.7	0.27	8.6	0.18	5.4	0.09	8.3	1.6	0.72	0.72
CaO	4.7	49.6	22.7	42.5	27.6	52.5	24.2	40.1	42.5	46.2
MgO	0.9	0.54	1.5	0.10	3.2	0.52	0.70	0.20	0.90	0.40
Na_2O	0.3	0.04	0.50	0.03	0.08	0.02	0.16	0.05	0.05	0.04
K_2O	2.6	0.17	1.1	0.05	0.24	0.14	1.2	0.29	0.07	0.21
TiO_2	1.5	< 0.02	0.26	< 0.02	0.32	< 0.02	0.79	0.11	< 0.02	< 0.02
P_2O_5	0.3	0.05	0.11	0.06	0.08	0.13	0.19	0.08	0.06	0.07
CO_2	2.6	29.2	5.3	3.7	7.2	36.6	15.3	13.6	11.5	24.4
SO_2	-	11.7	5.8	38.8	2.2	6.3	3.4	5.4	24.1	13.7
SO_3	0.8	3.5	6.5	3.3	12.3	0.5	< 0.1	24.9	8.4	4.4
$CaCO_3$	5.9	65.7	12.0	8.4	16.3	80.6	34.7	30.9	26.1	55.4

[a] Standards are identified in Table C-9.

Source: 144.

TABLE C-9. IDENTIFICATION OF APCS SLUDGE STANDARDS

Standard	Description
I	Fly ash from Connecticut Light and Power Company's Devon Station.
II	C-E sludge[a]--$CaCO_3$. 150% of stoichiometric. 2,000 ppm SO_2.
III	Kansas Power and Light sludge.
IV	C-E sludge--$Ca(OH)_2$. 38% to 50% of stoichiometric. 50 to 60% SO_2 removal. Slurry feed 830 liters/min. Recycle 625 liters/min with 210 liters/min blowdown.
V	Union Electric sludge.
VI	C-E sludge--$CaCO_3$. 150% of stoichiometric. 45 to 55% removal. No recycle.
VIA	Standard VI plus 50% Standard I (fly ash).
VII	C-E sludge--300 to 325% of stoichiometric. 64% SO_2 removal. 135 kg/hr fly ash. 250 kg $CaCO_3$.
VIII	C-E sludge—120 to 130% of stoichiometric $Ca(OH)_2$. 90.8% removal. 450 liters/min $Ca(OH)_2$ slurry underbed. Inlet SO_2 860 to 840 ppm. Outlet SO_2 80 ppm. 65 kg/hr $Ca(OH)_2$. No fly ash addition.
IX	C-E sludge--830 liters/min H_2O spray. 125 kg/hr lime feed. 150 C reaction temperature.

[a] Sludge from the Combustion Engineering pilot plant.

Source: 144.

TABLE C-10. X-RAY ANALYSIS OF APCS SLUDGES

Standard	Major	Minor	Trace
I	SiO_2 $3Al_2O_3 \cdot 2SiO_2$	Fe_2O_3	$CaCO_3$ Fe_3O_4 $CaSO_4$
III	SiO_2	Fe_3O_4 $CaCO_3$ $2CaSO_3 \cdot H_2O$	$3Al_2O_3 \cdot SiO_2$ $Ca(OH)_2$ $CaSO_4$ MgO
IV	$2CsSO_3 \cdot H_2O$	--	SiO_2
V	SiO_2 $CaCO_3$	$CaSO_4 \cdot 2H_2O$	$Ca(OH)_2$ $2CaSO_3 \cdot H_2O$ Fe_3O_4 $3Al_2O_3 \cdot 2SiO_2$
VI	$CaCO_3$	$2CaSO_3 \cdot H_2O$	$CaSO_4$ SiO_2
VIA	$CaCO_3$	SiO_2 $2Al_2O_3 \cdot 2SiO_2$	$2CaSO_3 \cdot H_2O$ $CaSO_4$ Fe_2O_3
VII	$2CaSO_3 \cdot H_2O$	$CaCO_3$	$2CaSO_3 \cdot H_2O$ $CaSO_4 \cdot 2H_2O$ SiO_2
VIII	$2CaSO_3 \cdot H_2O$	$CaCO_3$	$Ca(OH)_2$ SiO_2
IX	$CaCO_3$	--	$2CaSO_3 \cdot H_2O$ SiO_2 $CaSO_4 \cdot 2H_2O$ Fe_2O_3 $Ca(OH)_2$

Source: 144.

APPENDIX D

DESCRIPTION OF FBC UNITS PROVIDING RESIDUES

Pope, Evans, and Robbins Process (Alexandria, Virginia)

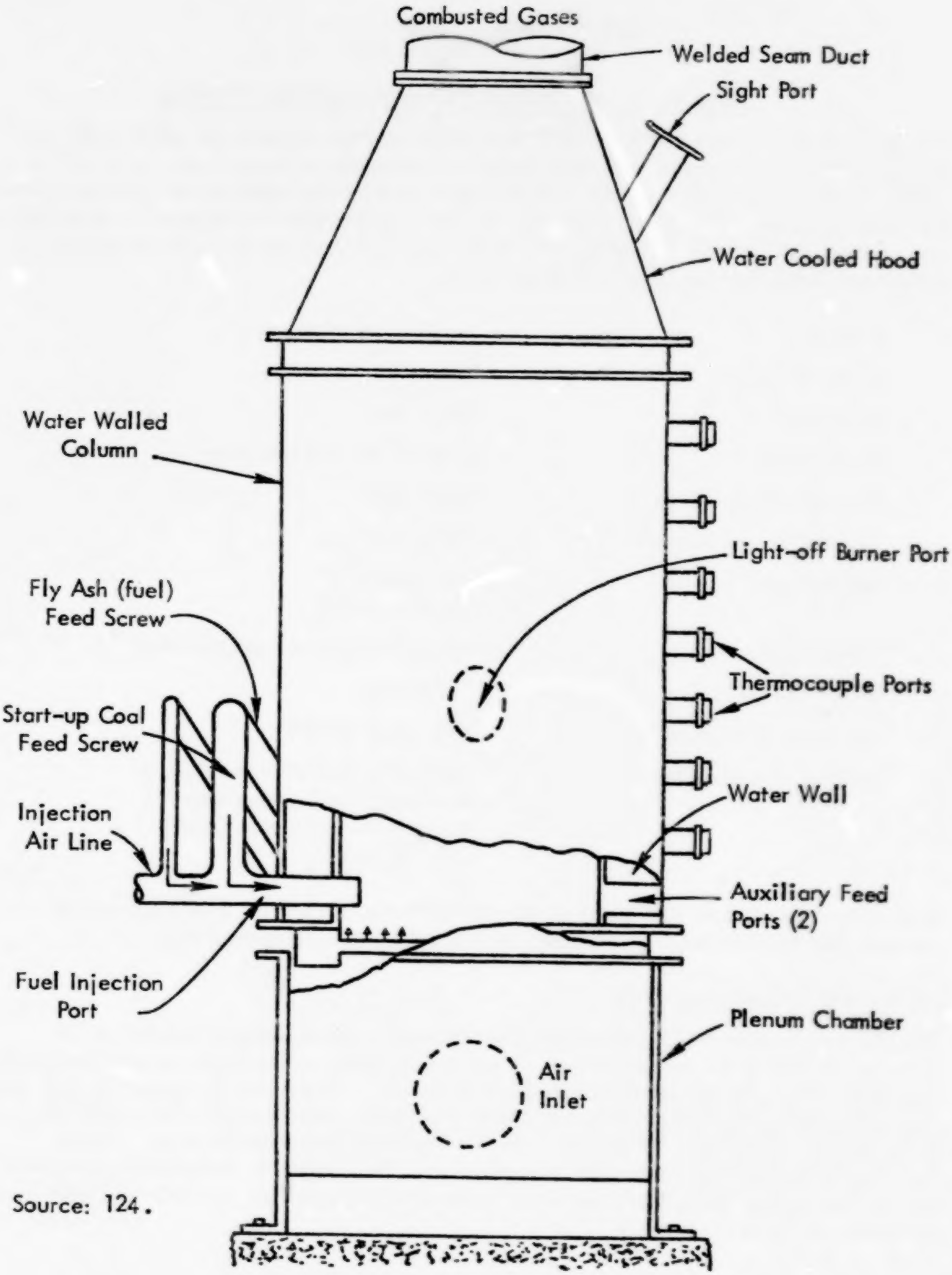
The U. S. Energy Research and Development Administration supports one pilot-scale and one full-scale fluidized-bed coal combustion unit operated by Pope, Evans, and Robbins (PER). In an earlier project on the PER unit (sponsored by the National Air Pollution Control Administration), they monitored air pollution emissions from the fluidized-bed combustion of coal under different conditions to determine those most favorable for reducing SO_2 emissions. Major test variables and ranges were:

Coal type	Medium and high sulfur
Bed temperature	815-1038° C
Bed depth	15-51 cm
Bed material	Sintered ash and limestone
Flue gas oxygen content	0.5-5.0%
Superficial gas velocity	1.8-4.3 m/sec
Sorbent type	Dolomite 1337 Limestone 1359
Sorbent state	Raw, hydrated, and precalcined
Sorbent particle size	7-325 mesh
Fly-ash recirculation	Full range (0-80%)
Method of sorbent feed	Pneumatic feed with the coal, pneumatic feed remote from the coal feed and pre-mixed with the coal

Tests were conducted on both pilot-scale and full-scale test units. This study tested residues from the full-scale unit located at Rivesville, West Virginia, only.

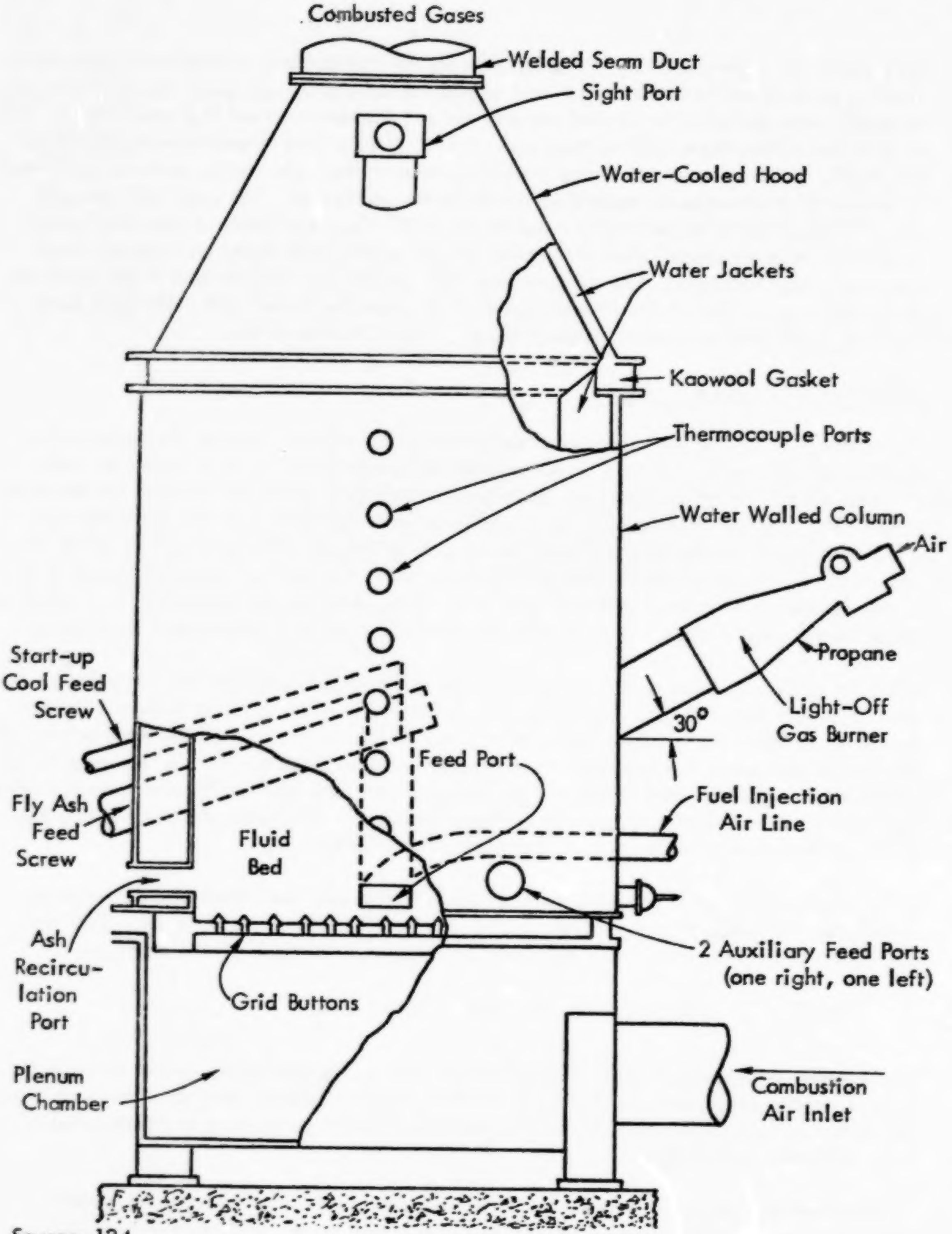
Fluidized-Bed Combustor (FBC)

The FBC tests explored SO_2 capture on a bench scale prior to a major expenditure of resources in testing the full-scale unit. Flue gas analyses, sulfur balances, and bed particle size versus time analyses were compiled for these tests. Portions of the operation also tested used salt addition for sorbent SO_2 activity enhancement, and for combustion catalysis in a once-through operation. The bench scale fluidized-bed combustor (FBC) contained a rectangular bed with dimensions 30.5 by 40.6 cm. The combustor was enclosed by an air distribution grid at the bottom, and water walls around the periphery. Side and front views are shown in Figures D-1 and D-2.


Combusted Gases
Welded Seam Duct
Sight Port
Water Cooled Hood
Water Walled Column
Light-off Burner Port
Fly Ash (fuel) Feed Screw
Thermocouple Ports
Start-up Coal Feed Screw
Water Wall
Injection Air Line
Auxiliary Feed Ports (2)
Fuel Injection Port
Plenum Chamber
Air Inlet

Source: 124.

Figure D-1. FBC construction detail (side view).


Combusted Gases
Welded Seam Duct
Sight Port
Water-Cooled Hood
Water Jackets
Kaowool Gasket
Thermocouple Ports
Water Walled Column
Air
Propane
Light-Off Gas Burner
30°
Start-up Coal Feed Screw
Fly Ash Feed Screw
Feed Port
Fuel Injection Air Line
Fluid Bed
2 Auxiliary Feed Ports (one right, one left)
Ash Recirculation Port
Grid Buttons
Plenum Chamber
Combustion Air Inlet

Source: 124.

FigureD-2: FBC construction detail (front view).

Air passed into a plenum below the grid, through the grid buttons, and into the combustion chamber to fluidize the bed material and to provide combustion oxygen. The bed material generally consisted of sintered coal ash crushed and double-screened to a mesh size of < 8 to > 14 (or of limestone 1359 of mesh size < 8 to > 20). Bed temperature depended on bed depth, which governed the total transfer surface at the water walls, and was monitored using several thermocouples spaced vertically in the combustor. The coal feed rate was about 50 kg per hour for an energy input of 3.4×10^5 kcal per hour. Before discharge, combustion products passed through a heavy gauge welded seam duct, an inducted draft fan, and a dust collector. The air flow rate was monitored by a Pitot tube in the entrance duct, and a gate valve in the line provided air flow control to the unit. The coal feed rate was controlled by a variable speed drive on the coal feed screw.

Full-Scale Boiler Module (FBM)

The rectangular bed of the sub-pilot scale atmospheric pressure unit had dimensions of 51 by 40.6 cm. It was contained in a rectangular enclosure in which each wall was a row of vertical boiler tubes seal-welded gas-tight. Figure D-3 shows the internal construction of the FBM. Its cross-section (46 by 183 cm) was roughly 7 times the FBC cross-section. Air was directed upward from a plenum at the base of the unit through a grid and into the bed area. Firing with a coal input of 363 kg per hour, the FBM produced 14 kg per sq cm (gauge) steam at the rate of 2,268 kg per hour. Coal feed was controlled by the rotation of a star feeder while sorbent material feed was controlled by a variable speed screw drive.

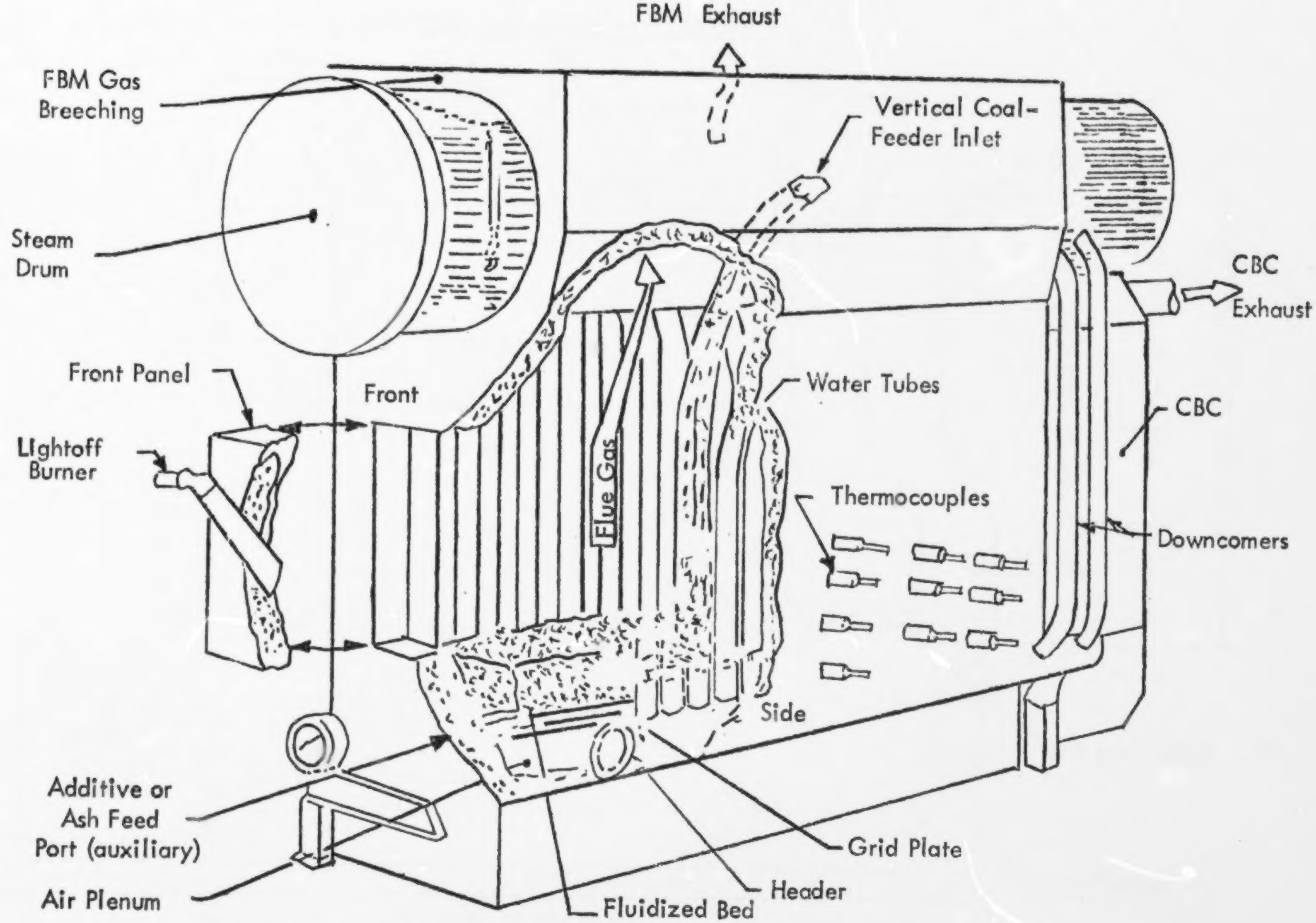
Ash circulation was by pneumatic transport from the dust collector through a star feeder control. Flue gas from the FBM was mixed with ambient air in the ducting above the unit to reduce its temperature before entering the air preheater. Fly ash which dropped out of the flue gas at that point was collected in the hopper. The bulk of the fly ash was retained in a multiclone collector downstream. From the collector, the flue gas flowed through a long duct to an induced-draft fan and then to the atmosphere. A balance damper was provided in this ducting to control pressure in the combustion chamber.

In the regenerator, sulfated limestone from the primary zone was circulated continuously so that the carbon-bearing fly ash was burned at 1092° C with low excess air. SO_2 was driven off in high concentrations and lime was recovered for reuse by the reaction:

$$CaSO_4 + C + 1/2\ O_2 \longrightarrow CaO + SO_2 + CO_2$$

Figure D-4 is the schematic flow diagram of the FBM and regenerator. Use of fuel gas for $CaSO_4$ regeneration was avoided for economic reasons. Several long-duration tests were conducted with the FBM to establish the effect of different parameters on the removal of SO_2 and other pollutants.

An experimental carbon burn-up cell (CBC) was added to the FBM to raise the system carbon burn-up from 90 percent into the 98-100 percent range,[6] and to determine the problems of operating with two distinct temperature zones (815° C in the FBM and 1,038° C


FBM Exhaust
FBM Gas Breeching
Vertical Coal-Feeder Inlet
Steam Drum
CBC Exhaust
Front Panel
Front
Water Tubes
CBC
Lightoff Burner
Flue Gas
Thermocouples
Downcomers
Side
Additive or Ash Feed Port (auxiliary)
Grid Plate
Air Plenum
Header
Fluidized Bed

Source: 124.

Figure D-3. Fluidized bed module: internal construction.

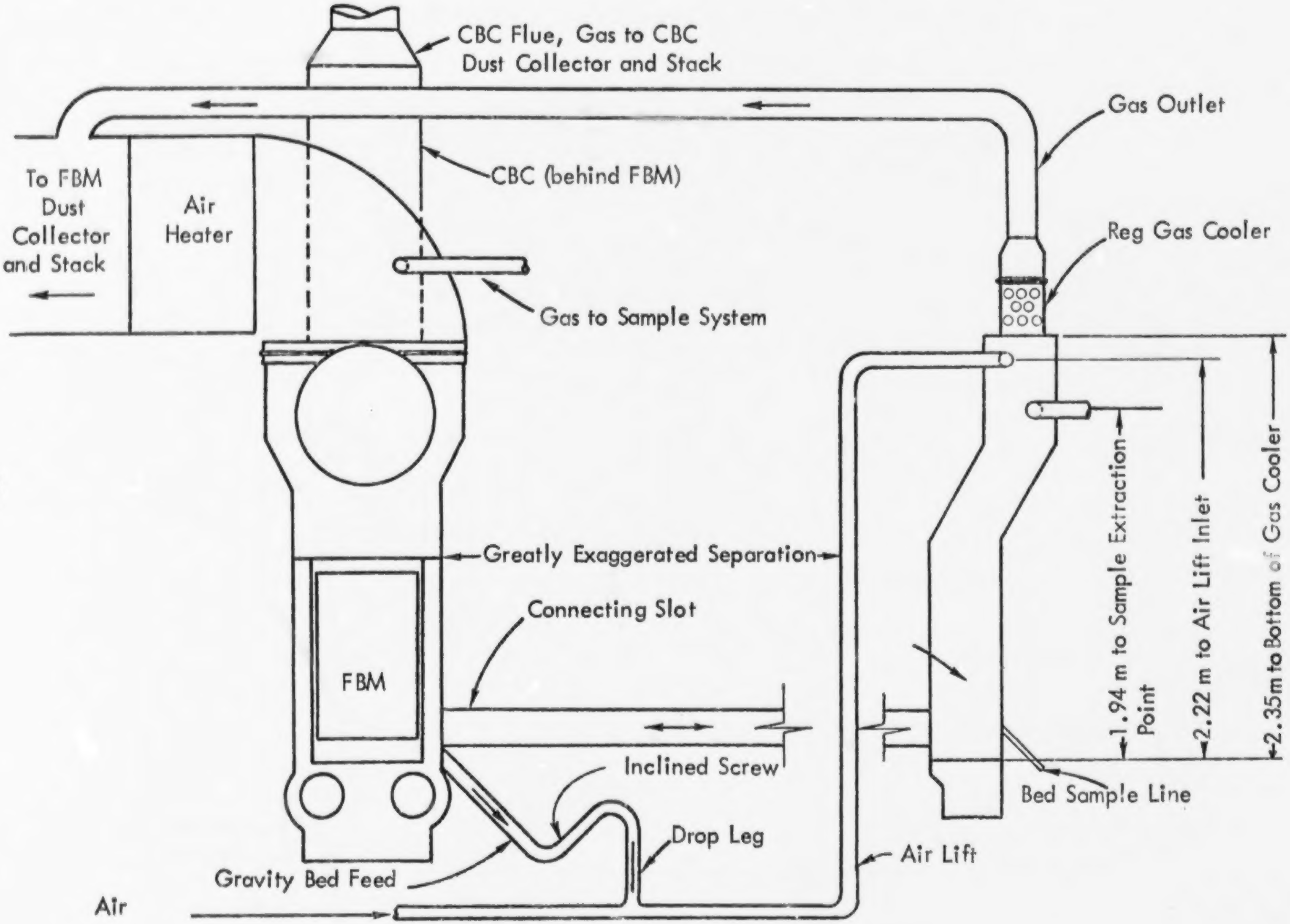

CBC Flue, Gas to CBC Dust Collector and Stack
Gas Outlet
To FBM Dust Collector and Stack
Air Heater
CBC (behind FBM)
Reg Gas Cooler
Gas to Sample System
Greatly Exaggerated Separation
Connecting Slot
FBM
1.94 m to Sample Extraction Point
2.22 m to Air Lift Inlet
2.35m to Bottom of Gas Cooler
Inclined Screw
Bed Sample Line
Drop Leg
Air Lift
Gravity Bed Feed
Air

Figure D-4. FBM and regenerator flow diagram.

Source: 121.

in the CBC). The CBC consisted of a chamber with a rectangular cross-section (27 by 40 cm). The uncooled insulated walls of the CBC were fabricated from 27 percent chromium steel. The CBC was an integral part of the FBM and was located at the back of the combustor under the steam drum. Figure D-5 is the section view of the integrated FBM/CBC unit. The CBC operated continuously and burned the carbon-containing fly ash from the FBM. Coal was fed with the fly ash when ash alone could not maintain the desired 1,038-1,149° C bed temperature. Fly ash from the CBC's own collector was also recycled during most tests. CBC emissions of hydrocarbons and carbon monoxide were essentially zero. Figure D-6 shows the flow path of bed material for the FBM, CBC, and regenerator.

Exxon Research and Engineering's Process (Linden, New Jersey)

The U. S. EPA (Office of Research and Development) sponsored a two-phase program to investigate the feasibility of producing large amounts of heat at low SO_x emission levels by burning coal under high pressure in a fluidized-bed of limestone. The first phase of the program involved the design and construction of a continuous fluidized-bed combustion/lime regeneration pilot unit--the FBCR miniplant (shown in Figure D-7). Design parameters of the process (mainly combustor and regenerator) are shown in Table D-1. The unit has been designed to operate at pressures up to 10 atmospheres with a heat release rate of about 1.5 million kcal per hour, equivalent to a power plant capacity of approximately 635 kilowatts.

The combustor was constructed from a 61 cm, refractory-lined pipe with a final inside diameter of 30 cm. It was designed with 5 flanged sections (each 90 cm long), a bottom plenum for air intake below the removable distributor plate, and an upper bed expansion section containing the gas discharge outlet to the cyclones. The regenerator was constructed from a 46-cm pipe, refractory lined to 13 cm internal diameter.

Fluidizing air to the combustor and regenerator was supplied by a stationary compressor with a capacity of 36.8 std cu m/min. Control valves and differential pressure transmitter controlled the superficial bed velocities. In the combustor, the air passed through the distributing grid and then the fluidized-bed, to a heat exchanger for cooling, and out through two refractory-lined cyclones for particulate removal. Air for the reducing-gas regenerator was electrically preheated. The reducing gas from the regenerator passed through a ceramic distributor plate supporting the regeneration bed, a refractory-lined cyclone, and a heat exchanger before being discharged through a butterfly valve. Pressure on the combustor and regenerator was kept constant by a differential pressure controlled by positioning the butterfly valve in the regenerator discharge line.

Heat extraction and temperature control in the fluidized-bed was accomplished by boiling water in the vertical zones of the reactor. Solids transfer between reactors and discharge from the regenerator was accomplished using a pulsed air transport technique controlled by pressure differentials across and between the fluidized-beds.

The second phase of the program involved a study of the factors influencing the formation and the control of nitrogen oxides (NO_x) in fluidized-bed combustion. For these studies, a 7.6 cm ID fluidized bed combustor and two smaller electrically heated fixed bed

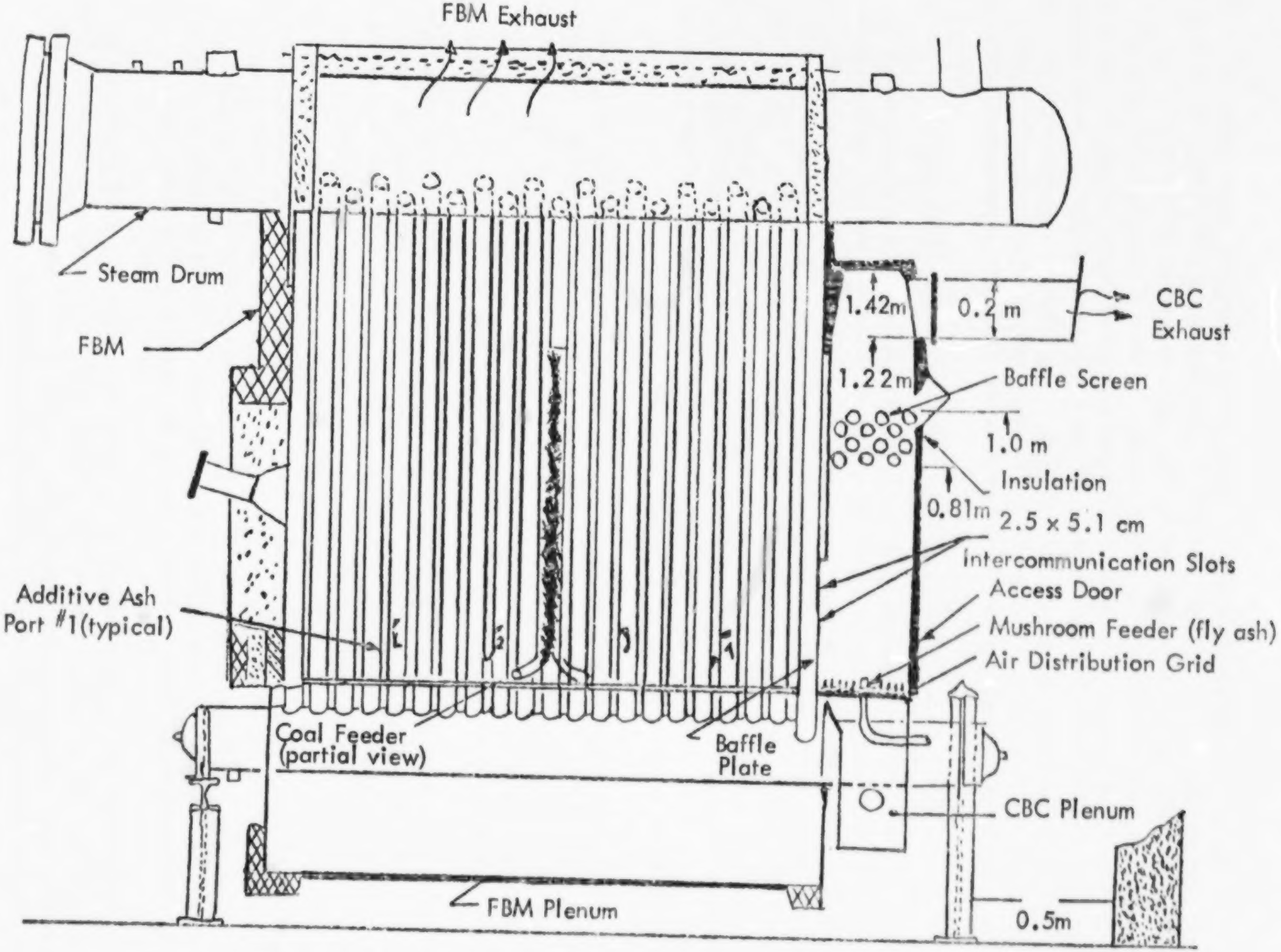
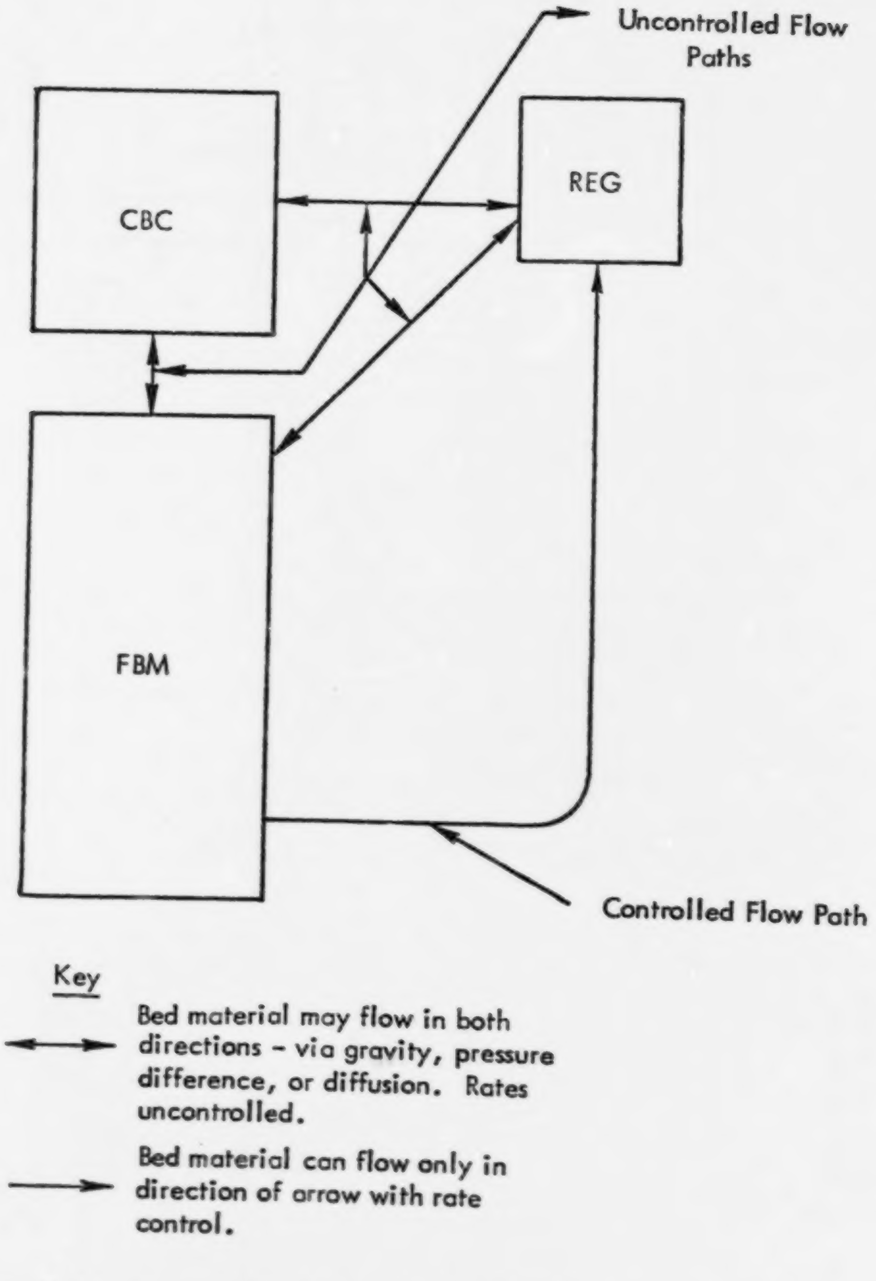

FBM Exhaust
Steam Drum
FBM
Additive Ash Port #1(typical)
Coal Feeder (partial view)
Baffle Plate
FBM Plenum
1.42m
1.22m
0.2 m
CBC Exhaust
Baffle Screen
1.0 m
Insulation
0.81m
2.5 x 5.1 cm
Intercommunication Slots
Access Door
Mushroom Feeder (fly ash)
Air Distribution Grid
CBC Plenum
0.5m

Figure D-5. Section view of the integrated FBM/CBC unit.

Source: 124.

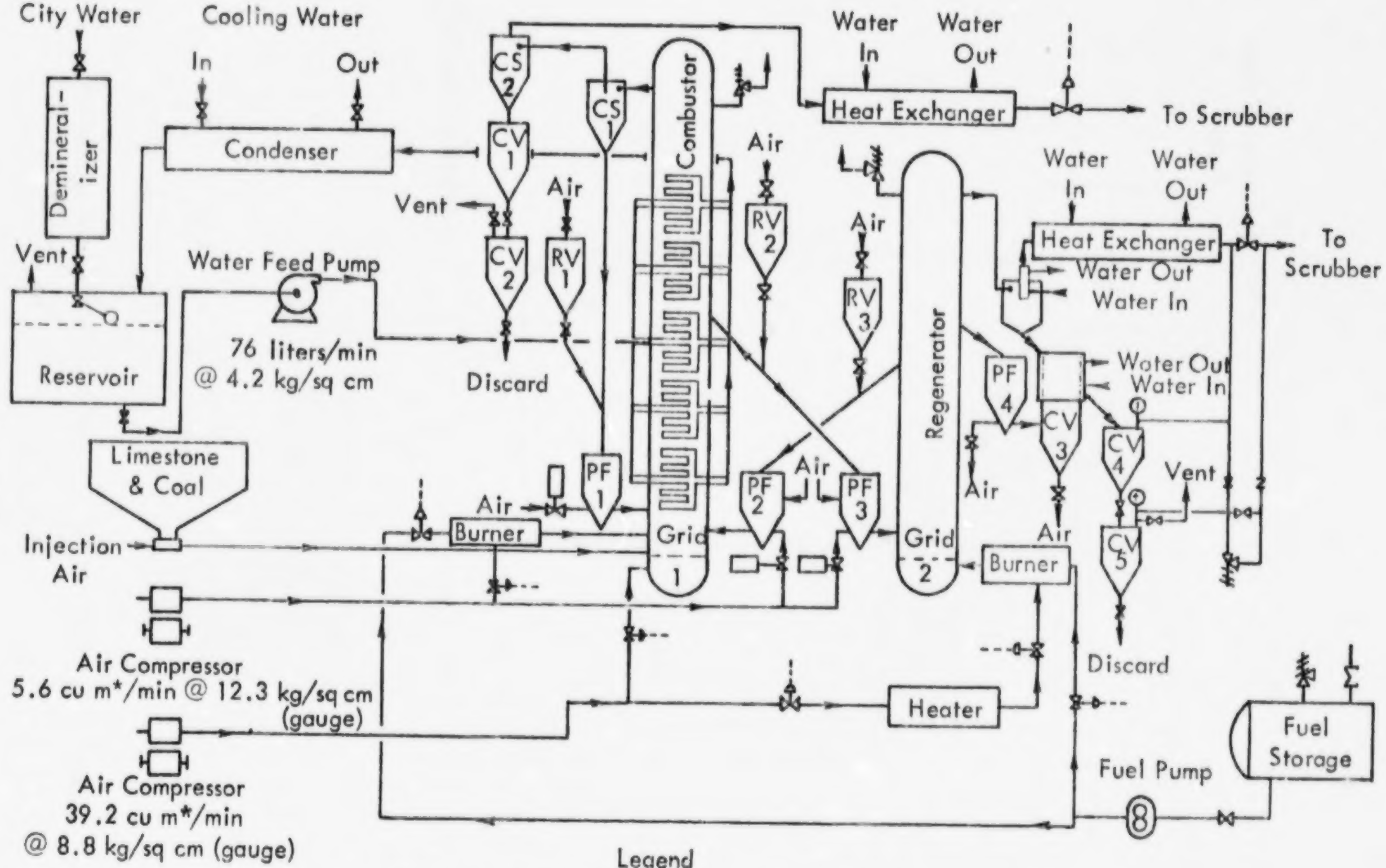

Uncontrolled Flow Paths
CBC
REG
FBM
Controlled Flow Path

Key

↔ Bed material may flow in both directions - via gravity, pressure difference, or diffusion. Rates uncontrolled.

→ Bed material can flow only in direction of arrow with rate control.

Source: 124. Figure D-6. Bed material flow paths: FBM, CBC and regenerator.


City Water
Cooling Water
In
Out
Demineral-izer
Condenser
Vent
Reservoir
Water Feed Pump
76 liters/min
@ 4.2 kg/sq cm
Limestone & Coal
Injection Air
Air Compressor
5.6 cu m*/min @ 12.3 kg/sq cm (gauge)
Air Compressor
39.2 cu m*/min
@ 8.8 kg/sq cm (gauge)
CS 2
CS 1
CV 1
CV 2
Vent
Discard
Air
RV 1
PF 1
Air
Burner
Combustor
Grid
1
Air
RV 2
Air
RV 3
PF 2
PF 3
Air
Regenerator
Grid
2
Water In
Water Out
Heat Exchanger
To Scrubber
Water In
Water Out
Heat Exchanger
To Scrubber
Water Out
Water In
PF 4
Air
Water Out
Water In
CV 3
CV 4
CV 5
Vent
Air
Burner
Discard
Heater
Fuel Pump
Fuel Storage

Legend

CS - Cyclone Separator PF - Pulse Feeder
CV - Collector Vessel RV - Refill Vessel

Figure D-7. Pressurized FBC pilot plant, Linden, New Jersey.

* At STP
Source: 43.

TABLE D-1 DESIGN PARAMETERS: EXXON MINIPLANT

Parameter	Unit	Component	
		Combustor	Regenerator
Unit dimensions			
Height	cm	71.10	48.30
Internal diameter	cm	31.75	12.70
Maximum operating conditions			
Temperature	°C	927	1,093
Pressure	atm	10	10
Superficial bed velocity	m/sec	3.05	1.52
Heat released by combustion	10^3 kcal/hr	1,588	--
Cooling load	10^3 kcal/hr	907	--
Maximum material rates			
Air	std cu m/min	33.98	2.55
Coal	kg/hr	218	--
Limestone	kg/hr	30.84	--
Natural gas	std cu m/min	--	0.28
SO_2 output	kg/hr	--	18.14

Source: 43.

reactors were used. An automatic instrument continuously measured NO, SO_2, and O_2 emissions. The operating factors that were studied included excess air level, temperature, and bed composition.

The 7.6-cm unit was modified to operate as a two-stage combustor, in order to test a reactor configuration that would yield low NO_x emissions by promoting the reduction of NO by CO and then the reaction of NO with SO_2 and lime. Operating at substoichiometric conditions, the NO-CO reaction was permitted and secondary air was added at a higher point in the bed to complete the combustion and provide SO_2 for reaction with the remaining NO. A schematic diagram of the Exxon fluid bed combustion unit is shown in Figure D-8.

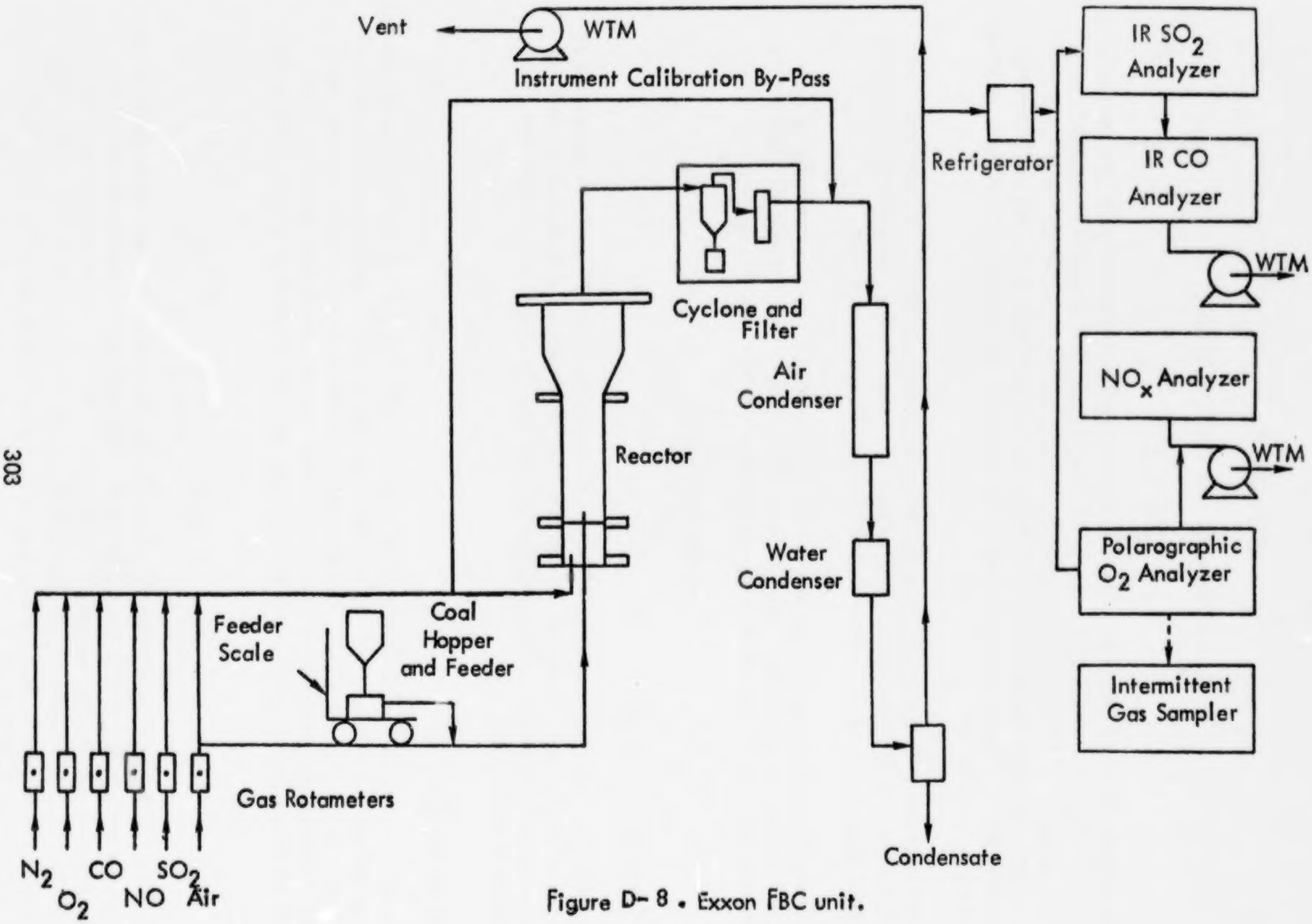

Vent
WTM
Instrument Calibration By-Pass
Refrigerator
IR SO_2 Analyzer
IR CO Analyzer
WTM
NO_x Analyzer
WTM
Polarographic O_2 Analyzer
Intermittent Gas Sampler
Cyclone and Filter
Air Condenser
Reactor
Water Condenser
Condensate
Coal Hopper and Feeder
Feeder Scale
Gas Rotameters
N_2
O_2
CO
NO
SO_2
Air

Figure D-8. Exxon FBC unit.

Source: 43

APPENDIX E

FLUIDIZED-BED OIL GASIFICATION

Introduction

Fluidized-bed oil gasification provides the technology for utilizing high-sulfur residual oils and asphalts for clean power generation. Oil can be gasified at either atmospheric or elevated pressure. At atmospheric pressure, a fluidized-bed gasifier provides clean fuel to a boiler. At elevated pressure, the fuel goes to a combined-cycle gas and steam turbine power plant. Power-cycle schematics for low and high pressure alternatives are shown in Figures E-1 and E-2.

Low and high pressure systems may use either once-through operation, or regeneration of the limestone or dolomite sorbent. The quality of waste material is minimized by keeping the spent sorbent dry, which makes it potentially suitable for other use.

The atmospheric (low) pressure process can be used to retrofit an existing boiler or as a design feature on a new boiler. Capital costs of a retrofit, once-through oil gasification system may be 50 to 70 percent less than a retrofit stack gas cleaning system.

Process Descriptions

Low-Pressure Gasification

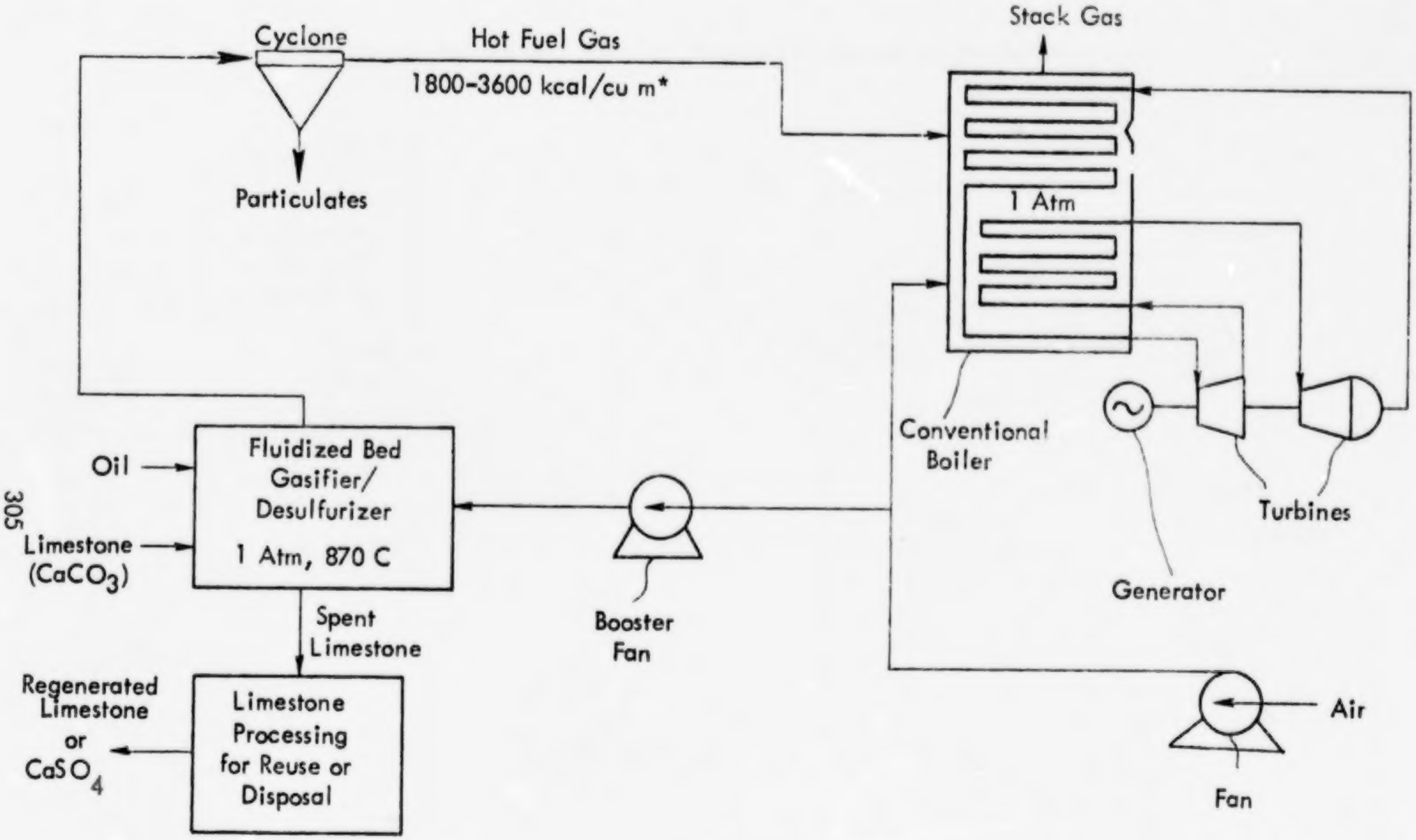
The gasification/desulfurization operation was accomplished by either the regenerative or the once-through mode. Figure E-3 illustrates the major process streams and elements of the two operational modes. The specifications assumed for design of a commercial plant are shown in Table E-1.

Regenerative Operation

The major components of the regenerative operation were the gasifier and regenerator vessels. The gasifier was an air-fluidized bed of lime operated at 870° C with substoichiometric air ($\approx$ 20 percent of stoichiometric). Heavy residual oil was injected into the gasifier vessel where it cracked and was partially combusted to form a hot, low-sulfur gas. Hydrogen sulfide produced during gasification reacted with the lime to produce calcium sulfide and water:

$$H_2S + CaO \longrightarrow CaS + H_2O$$

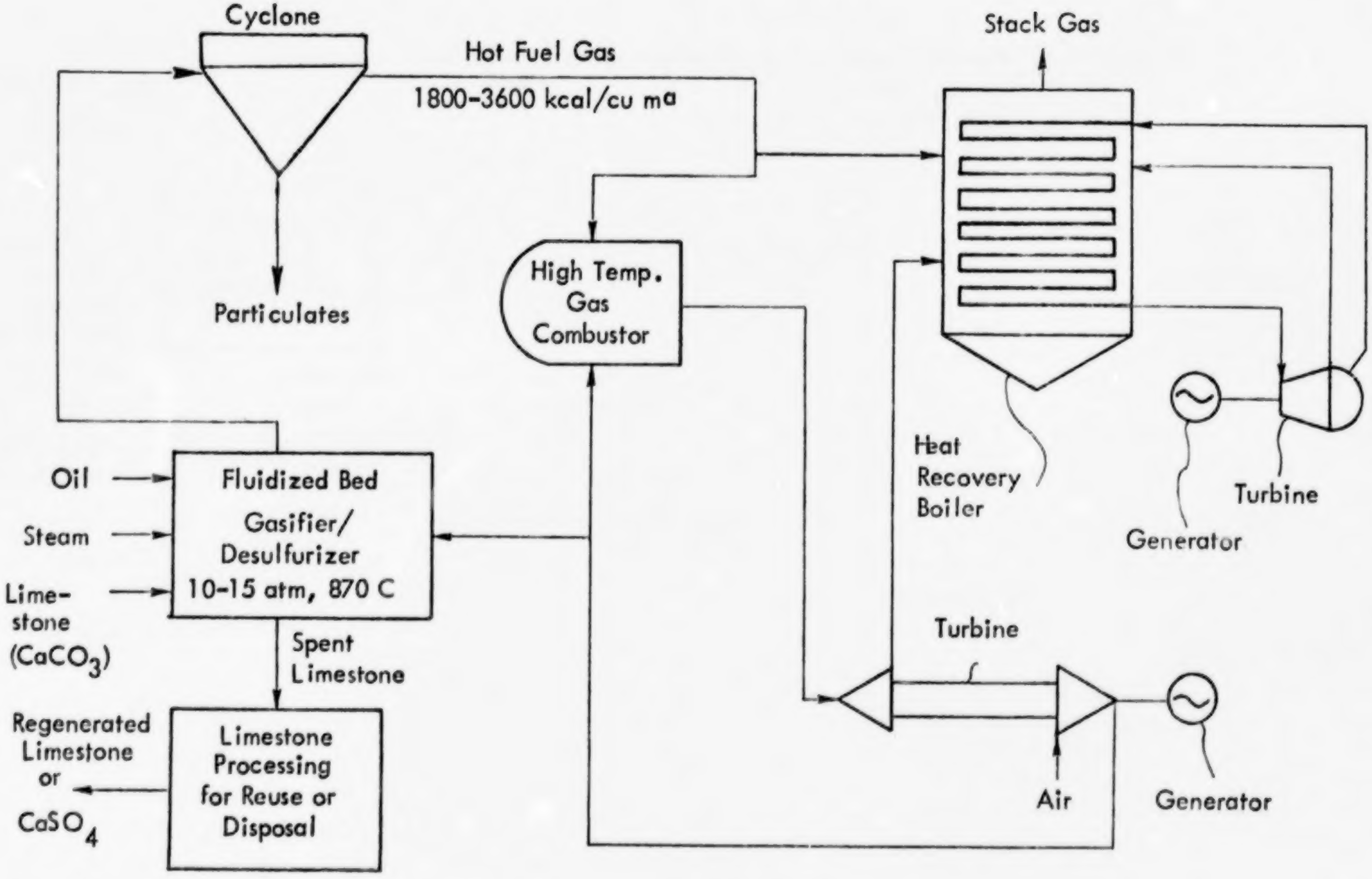
The hot fuel gas was transported to the boiler burners where combustion was completed, and the calcium sulfide was sent to the regenerator. The regenerator was an air-fluidized vessel operated with a slight excess of air at about 1,000° C. Regeneration took place by the reaction of oxygen with the calcium sulfide (spent lime) to give an SO_2 rich stream (of about 10 mole percent SO_2) and a regenerated lime having a slightly decreased activity compared to that of fresh lime:


Cyclone
Hot Fuel Gas
1800-3600 kcal/cu m*
Particulates
Stack Gas
1 Atm
Conventional Boiler
Generator
Turbines
Oil
Limestone (CaCO3)
Fluidized Bed Gasifier/ Desulfurizer
1 Atm, 870 C
Spent Limestone
Booster Fan
Regenerated Limestone or CaSO4
Limestone Processing for Reuse or Disposal
Air
Fan

* At STP.

Source: 104.

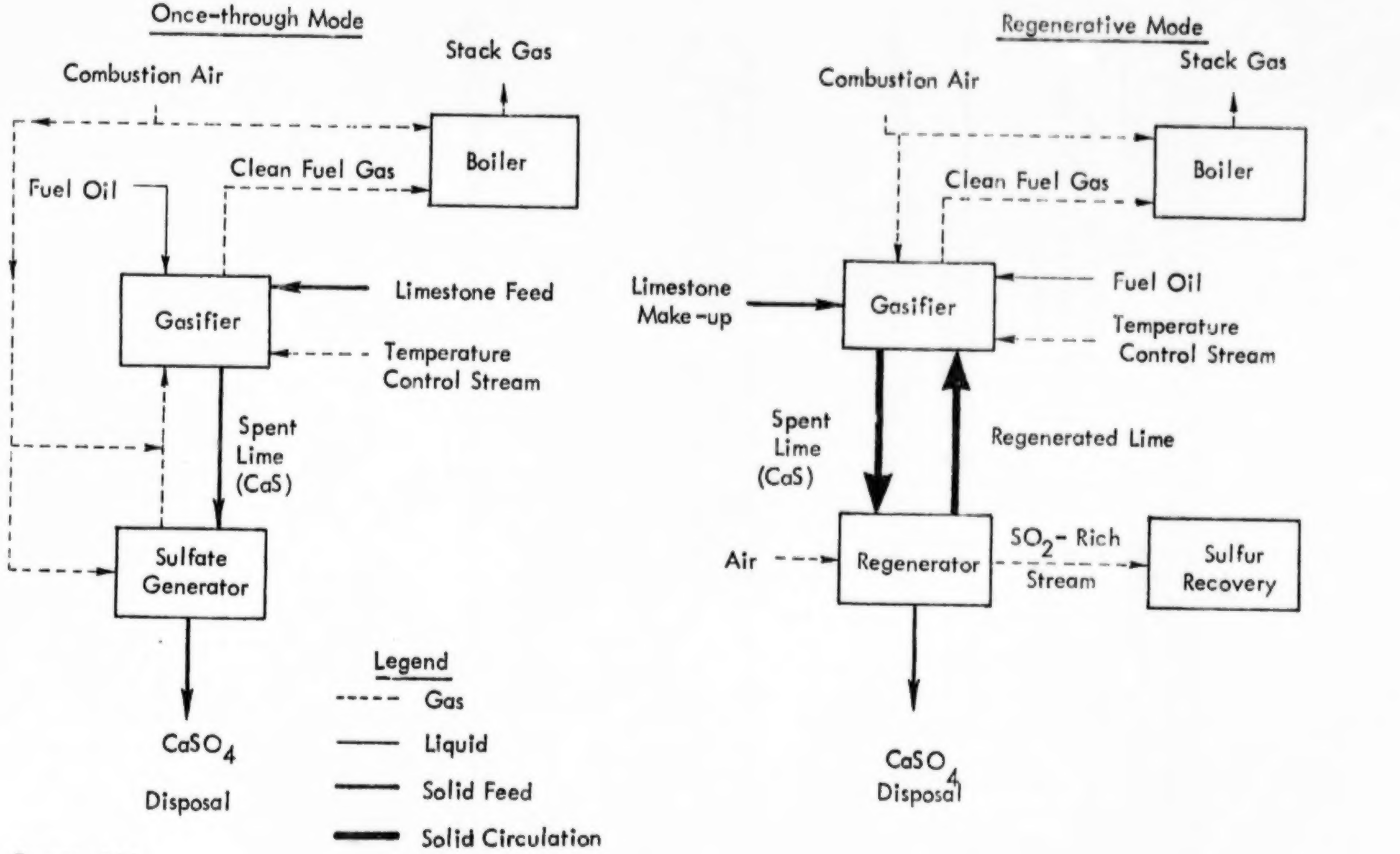
Figure E-1. Low pressure fluidized bed oil gasification for power generation.


Cyclone
Hot Fuel Gas
1800-3600 kcal/cu m[a]
Stack Gas
Particulates
High Temp. Gas Combustor
Heat Recovery Boiler
Turbine
Generator
Oil
Steam
Lime-stone ($CaCO_3$)
Fluidized Bed Gasifier/ Desulfurizer 10-15 atm, 870 C
Spent Limestone
Turbine
Regenerated Limestone or $CaSO_4$
Limestone Processing for Reuse or Disposal
Air
Generator

[a] At STP.

Figure E-2. High pressure fluidized bed oil gasification for power generation.

Source. 104.


Once-through Mode
Combustion Air
Stack Gas
Boiler
Clean Fuel Gas
Fuel Oil
Gasifier
Limestone Feed
Temperature Control Stream
Spent Lime (CaS)
Sulfate Generator
$CaSO_4$ Disposal
Legend
Gas
Liquid
Solid Feed
Solid Circulation
Regenerative Mode
Combustion Air
Stack Gas
Boiler
Clean Fuel Gas
Limestone Make-up
Gasifier
Fuel Oil
Temperature Control Stream
Spent Lime (CaS)
Regenerated Lime
Air
Regenerator
SO_2- Rich Stream
Sulfur Recovery
$CaSO_4$ Disposal

Source: 104.

Figure E-3. Modes of operation, fluidized bed oil gasification plant.

TABLE E-1. ATMOSPHERIC PRESSURE OIL GASIFICATION SPECIFICATIONS

Process Specifications	Design Variables
Sulfur Removal: 90-95%	Boiler Size: 600 Mw
Fuel Oil: 3% sulfur by wt.; LHV = 9.81×10^3 kcal/kg	Load Factor: 40%, 80%
Limestone: 98.6% CaO yield	Turndown: 4/1

Parameter	Operating Variables	
	Regenerative System	Once-Through System
Gasifier temperature (°C)	870	870
Regenerator (sulfate generator) temperature (°C)	1,000	820
Limestone make-up rate	1 mole CaO/mole sulfur	3 moles CaO/mole sulfur
Air/fuel ratio	20% of stoichiometric	20% of stoichiometric
Limestone utilization	5% sulfur by wt. in bed	19% sulfur by wt. in bed
Fluidization velocity (m/sec)	2.4	2.4
Minimum fluidization velocity (m/sec)	0.9	0.3
Particle sizes, avg. (μ)	2,000	1,000
Gasifier bed depth, static (m)	0.8 - 1.1	1.1 - 1.2

Source: 104.

$$CaS + 3/2\,O_2 \longrightarrow CaO + SO_2$$

The SO_2 stream was transported to a sulfur recovery system, and the regenerated lime was returned to the gasifier along with an approximately stoichiometric amount of fresh make-up limestone.

Once-Through Operation. The elements of the once-through operation were a gasifier vessel and a sulfate generator, or a predisposal vessel. The operation of the gasifier was the same as for the regenerative operation. The sulfate generator operated similarly to the regenerator but a a lower temperature (≈ 800° C), so that the calcium sulfide from the gasifier was converted to calcium sulfate rather than calcium oxide. The dry calcium sulfate was disposed of, and the gas stream from the sulfate generator was sent to the gasifier. A limestone addition rate of up to three times that used in the regenerative operation was necessary to achieve sulfur removal of 90 to 95 percent.

High-Pressure Combined-Cycle Gasification

The high pressure combined-cycle gasification process was accomplished by either once-through or regenerative operation. Table E-2 lists the factors specified for the conceptual design of the high pressure fluid-bed oil gasification process. Figure E-4 shows a flow diagram of the energy balances for the high pressure fluid-bed oil gasification process.

Regenerative Operation. The high pressure regenerative process shown in Figure E-5 consists of a fluidized-bed gasifier/desulfurizer vessel, a limestone/dolomite regenerator, and a sulfur recovery section. Residual oil was injected into the gasifier vessel and fluidized-bed of lime operated at 870° C with substoichiometric air (14 to 25 percent of stoichiometric). This yielded (by cracking,partial combustion, and H_2S absorption by the limestone or dolomite) a hot fuel gas of low energy value and sulfided lime or dolomite. The gas was transported to the combined cycle plant where combustion was completed, and the sulfided lime or dolomite was sent to the regenerator. The regenerator may be designed to produce gas rich in H_2S or SO_2 and regenerated sorbent with a decreased activity. The SO_2 or H_2S stream was transported to a sulfur recovery system, and the regenerated sorbent was returned to the gasifier along with a nearly stoichiometric amount of fresh make-up sorbent.

The regeneration of calcium sulfide and the production of a high-sulfur gas for recovery can be achieved by either of two processes, as follows:

1) Regeneration with CO_2 and H_2O to produce H_2S:

$$CaS + H_2O + CO_2 \longrightarrow CaCO_3 + H_2S$$

2) Regeneration with air to produce SO_2:

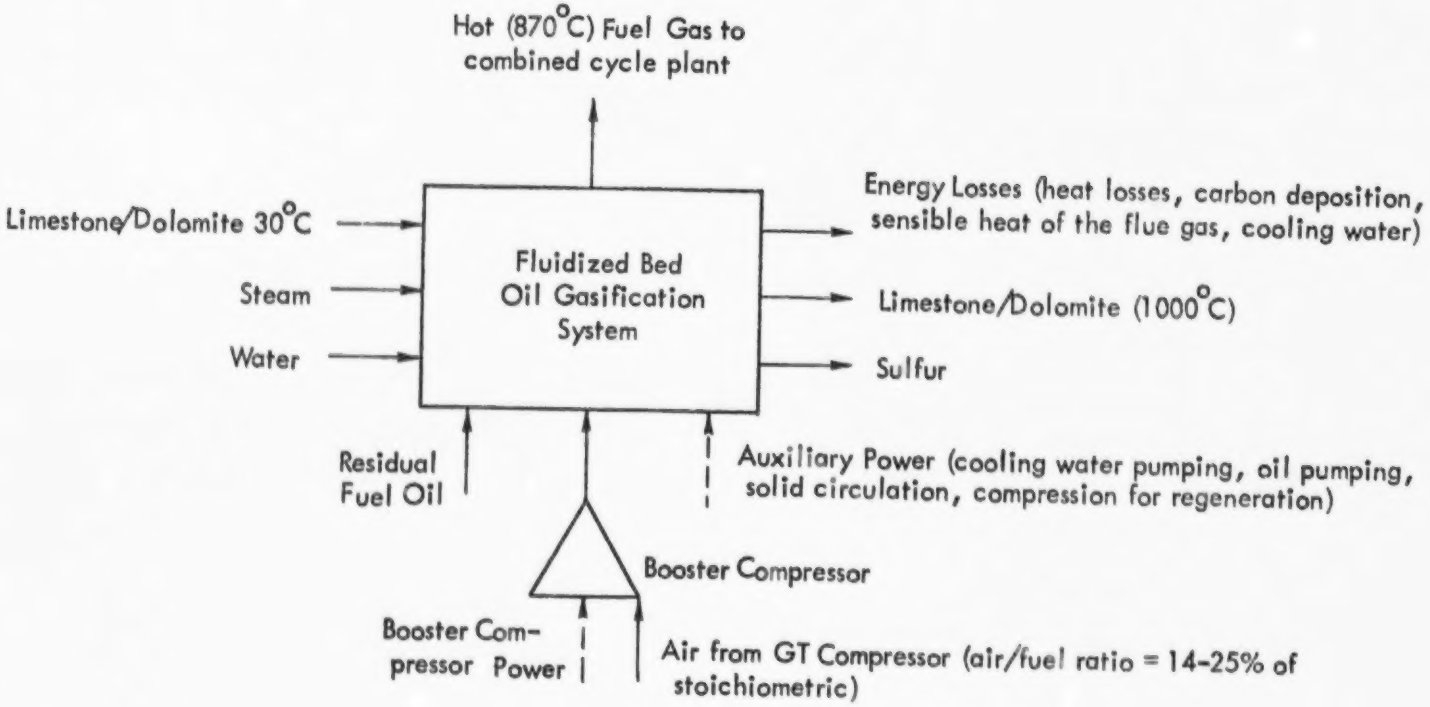
$$CaS + 3/2\,O_2 \longrightarrow CaO + SO_2$$

TABLE E-2. SPECIFICATIONS FOR HIGH PRESSURE FLUIDIZED BED OPERATION

Item	Specification
Plant electrical capacity	250 Mw (PACE Plant)
Capacity factor	70%
Turndown ratio	4/1
Number of gasifier modules	2
Modes of operation	Regenerative or once-through
Gasifier pressure	~ 15 atm
Pressure of gas turbine	11 atm (11.6 kgf/sq cm to turbine)
Sulfur removal	90-95%
Residual oil	3 wt % sulfur
Gasifier temperature	870 C
Regenerator temperature	600 C[a]
Sulfate generator temperature	930 C with once-through option
Air/fuel ratios	14 (minimum) & 25% stoichiometric
Lime particle diameters	500-2000μ average diameter
Regenerative lime utilization	10%
Once-through lime utilization	35%
Limestone make-up rate	1 mole CaO/mole sulfur fed
Gasifier temperature control	Stack gas recycle, steam or water injection
Regenerator temperature control	Lime circulation rate; water injection
Sulfate generator temperature control	Excess air circulation (~200% excess)
Plant heat rate	2300 kcal/kwh (assumed for purposes of material balances)

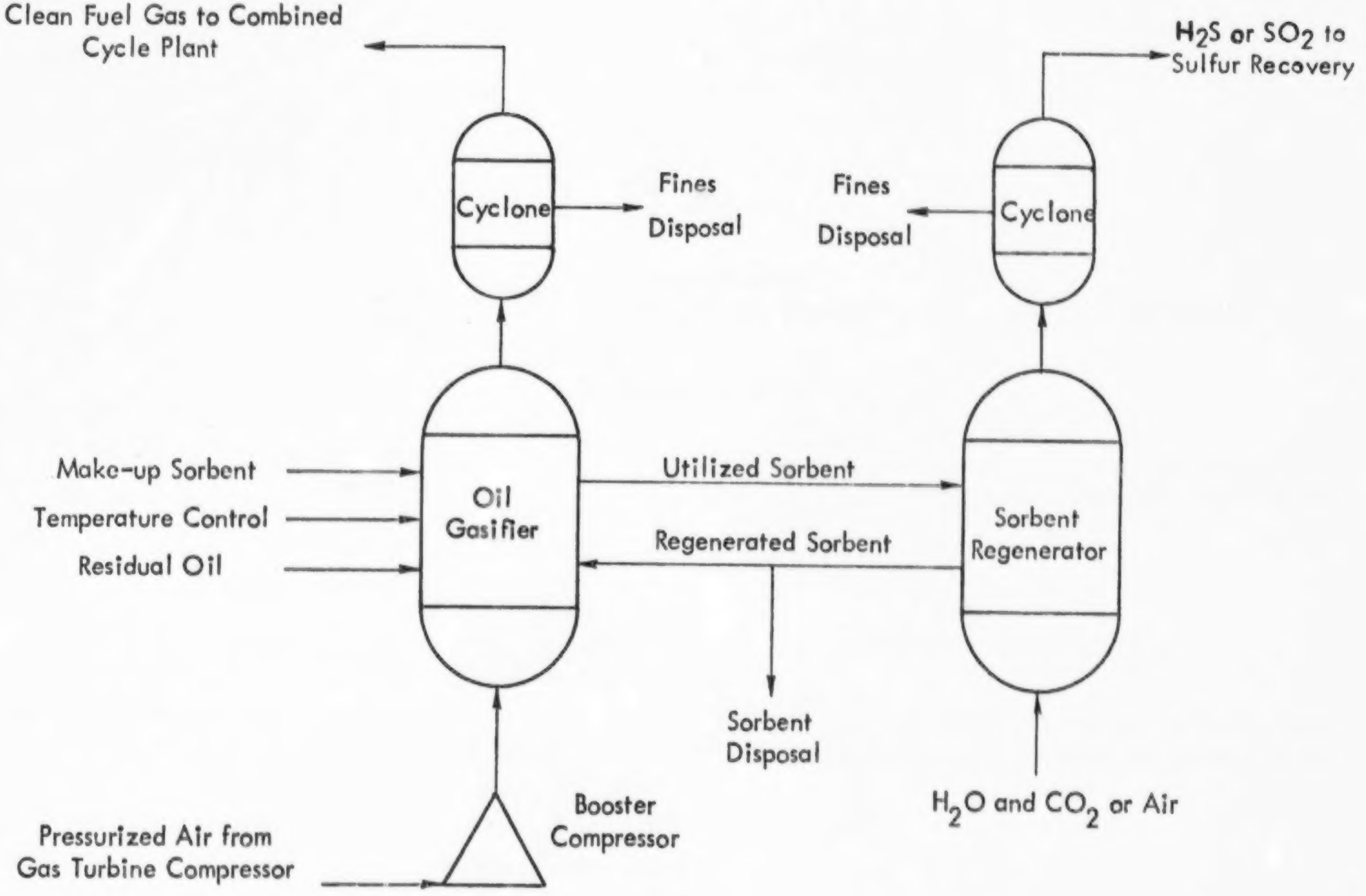
[a] With CO_2/H_2O regeneration; 1150 C with air regeneration.

Source: 104.


Hot (870°C) Fuel Gas to combined cycle plant
Limestone/Dolomite 30°C
Steam
Water
Fluidized Bed Oil Gasification System
Energy Losses (heat losses, carbon deposition, sensible heat of the flue gas, cooling water)
Limestone/Dolomite (1000°C)
Sulfur
Residual Fuel Oil
Auxiliary Power (cooling water pumping, oil pumping, solid circulation, compression for regeneration)
Booster Compressor
Booster Compressor Power
Air from GT Compressor (air/fuel ratio = 14-25% of stoichiometric)

Source: 104.

Figure E-4 . Energy balances flow diagram.



Clean Fuel Gas to Combined Cycle Plant
H_2S or SO_2 to Sulfur Recovery
Cyclone
Fines Disposal
Fines Disposal
Cyclone
Make-up Sorbent
Temperature Control
Residual Oil
Oil Gasifier
Utilized Sorbent
Regenerated Sorbent
Sorbent Regenerator
Sorbent Disposal
Pressurized Air from Gas Turbine Compressor
Booster Compressor
H_2O and CO_2 or Air

Source: 104.

Figure E-5 . Regenerative high-pressure oil gasification process.

Table E-3 lists the gasification product compositions and fuel heat values for a high-pressure fluidized-bed gasification system with limestone regeneration.

Once-Through Operation. If a high sorbent make-up rate is required for the regenerative processes and if high sorbent utilization can be achieved in the gasifier, a once-through system may be attractive. A flow diagram of the once-through system is presented in Figure E-4. Once-through operation would require conversion of calcium sulfide to calcium sulfate before disposal of the sorbent. The reaction is:

$$CaS + 2O_2 \longrightarrow CaSO_4.$$

Process Environmental Comparison

Table E-4 compares environmental factors for power generation by oil gasification (with a conventional plant or with a combined-cycle steam and gas turbine plant) with the environmental effects of a conventional oil-fired power plant using limestone scrubbing.

The spent sorbent from the fluidized bed oil gasification/desulfurization process was dry and granular ($\approx$ 6 mm). The composition was primarily calcium oxide and calcium sulfide with small amounts of calcium sulfate--the spent stone from regenerative operation containing approximately 1 to 2 percent CaS and, from once-through operation, a projection of 30 to 80 percent CaS. Table E-5 lists some advantages of low-pressure oil gasification over stack gas wet scrubbers.

Preliminary indications suggest that the once-through operation may be somewhat more attractive to a utility than the regenerative operation.

Esso Research Center's Process (Abingdon,Great Britain)

CAFB Pilot Plant

The Chemically Active Fluid-Bed (CAFB) developed by Esso reduces sulfur oxide pollution while using high sulfur oil to produce power. The process used a fluidized-bed of lime particles to convert the oil into a hot,low sulfur gas ready for combustion in an adjacent boiler. The process had the additional benefit of removing vanadium before the final combustion states and thus eliminating a source of internal boiler corrosion.

When oil was combusted under sub-stoichiometric conditions, the sulfur was trapped by lime as calcium sulfide:

$$H_2S + CaO \longrightarrow CaS + H_2O$$

CaS formed by the reaction of H_2S and CaO in the gasifier fluid-bed was converted back to CaO in a fluid-bed regenerator by contact with air:

$$CaS + 3/2\ O_2 \longrightarrow CaO + SO_2$$

TABLE E-3. GASIFICATION PRODUCT COMPOSITIONS

Gas	Composition (% by volume)	
	14% A/F[a]	25% A/F
N_2	50.74	47.74
H_2	0.82	2.64
CO	13.40	7.97
CO_2	6.70	7.97
H_2O	0.00	20.56
CH_4	9.43	6.55
C_2H_4	18.86	6.55
H_2S	0.05	0.02
Low heating value (hot) (10^3 kcal/cu m)	~ 70	~ 40

[a] Air/fuel ratio.

Source: 104.

TABLE E-4. ENVIRONMENTAL IMPACT COMPARISON

Environmental Factors	Conventional Oil-Fired Power Plant with Limestone Wet Scrubbing	Conventional Oil-Fired Plant with Atm-Pressure Oil Gasification		Combined Cycle Power Plant with Pressurized Oil Gasification	
		Regenerative	Once-through	Regenerative	Once-through
Plant capital investment ($/kw)	325	310	300	180	160
Plant energy cost (mills/kwhr)	13.1	12.7	12.5	9.7	9.2
Limestone waste (kkg/day)	440 (sludge)	80-160	450-730	80-160	450-700
Water usage (kkg/day)	450 (sludge)	-	-	-	-
SO_2 emission (kg/10^6 kcal)	0.63	0.63	0.63	0.63	0.63
NO_x emission (kg/10^6 kcal)	1.44	0.29	0.29	0.29	0.29
Particulate emission (kg/10^6 kcal)	0.04	0.04	0.04	0.04	0.04
Thermal emission (% of conventional plant)	100	~ 100	~ 100	~ 50	~ 50
Auxiliary power & fuel (% of plant input)	4.0	2.5	2.5	7.5	5.0
Plant heat rate (kcal/kwhr)	2,400	2,400	2,400	2,400	2,300
Land requirement	large area for disposal pond	large area	large area	more compact power plant	

Basis: 635 Mw power plant @ 1973 costs; capitalization at 15%; residual oil at \$1.79/10^6 kcal; gasification at air/fuel ratio of 20% of stoichiometric; limestone make-up rate of 0.5 to 1.0 times stoichiometric for regeneration and 1.5 to 3.0 times stoichiometric for once-through; for wet scrubbing a make-up rate of 1.2 times stoichiometric; NO_x emission for gasifier based on pilot plant measurements; combined cycle plant based on conventional gas-turbine technology, advanced gas turbine conditions can reduce plant costs and total emissions; gasification process consists of two independent gasifier modules.

Source: 104.

TABLE E-5. ADVANTAGES OF ATMOSPHERIC PRESSURE OIL GASIFICATION OVER STACK GAS WET SCRUBBERS

1. Corrosion and fouling problems minimized in SO_2 removal process and in boiler (minimum SO_x and V)
2. No flue gas reheat required.
3. Uses crushed limestone – no limestone pulverizing system needed.
4. Simplified disposal – dry solids and no disposal pond.
5. More compact system.
6. Reduced structural costs.
7. Lower auxilary power requirement.
8. Reduced energy cost.
9. Improved NO_x control.
10. Potential market for spent CaO

Source: 104.

The amount of regenerated lime removed was made up by the addition of fresh limestone to the combustor; sulfur was recovered during the regeneration process in several ways, such as conversion to H_2SO_4 or elemental sulfur.

The main unit of the CAFB process was the combustor and regenerator system which was made of an insulated steel shell contained in a refractory concrete cast. The gasifier and regenerator were cavities in a single refractory concrete block. One block contained other cavities which made up the gasifier outlet cyclones, the gas transfer ducts, and transfer lines through which solids circulated. The gasifier product gas fired a 2,930 kw pressurized water boiler. The hot water was heat-exchanged through a forced convection cooling tower. The rest of the system consisted of the necessary blowers, pumps, and instruments to operate the gasifier, regenerator, burner, and solid circulation system.

Batch Reactor and CAFB Experiments

Under contract to EPA's Office of Research and Development, Esso investigated sulfur absorption and lime regeneration operating variables. The experimental equipment used in the study consisted of two batch reactor units and the continuous CAFB pilot plant. Changes were made to various sections between test runs as a result of experience and to achieve specific objectives. The oils used were heavy fuel oils from Venezuela crudes obtained from the Amuary Refinery of the Crude Petroleum Co. Pilot plant runs had employed U.S. Stone BCR 1691 and a U.K. limestone from Denbighshire Batch units had employed the latter two stones, as well as U.S. Stone BCR 1359. A summary of the experimental results appears in Table E-6.

Each batch unit contained a reactor, air and fuel systems, a flare for product gas disposal, and a gas sampling and analysis system, as shown in Figure E-6. The reactors were made of stainless steel with a refractory lining. The lower section, which contained the fluid bed, was 17.8 cm (ID) by 84 cm high. The reactors used in the original tests were not fitted with cyclones and, therefore, were used only in low gas velocity experiments. The unit had no provision for temperature control other than by adjusting the quantity of insulation around the reactor. The insulation was arranged to permit the unit to operate in the range of 800 to 900° C with air velocity of 1.2 m/sec and an excess of over 30 percent to that required for combustion.

When operating under combustion conditions and also during regeneration of bed material, the gas from the bed was monitored directly for CO_2, CO, O_2 and for appropriate information on combustion efficiency, sulfur removal efficiency, or sulfur release deduced. During gasification, a portion of the product gas was burned in a sample flame located just above the reactor, and the combustion products were analyzed for SO_2, O_2, CO, and CO_2. The desulfurizing efficiency of the gasifier was calculated from the analysis of the fully combusted gas. The first reactors were used in the initial fuel oil screening work; the two later batch reactors were designed and constructed for studies of various operating modes.

TABLE E-6. SUMMARY OF EXPERIMENTAL RESULTS

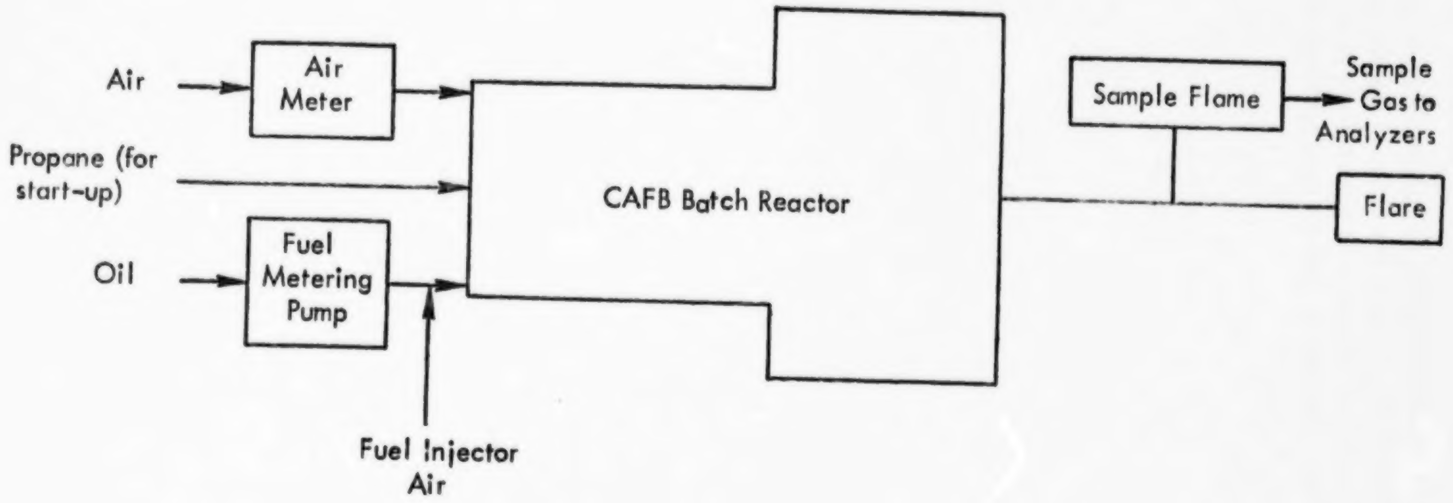
Batch Tests

1. Nearly 100% sulfur removal at 870 C, 20% air/fuel ratio, with limestone make-up rate of 1 mole CaO/mole of sulfur bed.
2. Nearly 100% of fuel vanadium removed.
3. About 20% of fuel sodium removed.
4. Clean product fuel is easily combustible with a luminous smoke-free flame.
5. Regeneration at 1000 C gives a 10% SO_2-gas product and a regenerated lime having reduced activity.

Continuous Unit

1. Results indicate superior behavior during continuous operation due to the improved temperature control.
    - Lower air/fuel ratios, down to 17% of stoichiometric, have been demonstrated.
    - 90% sulfur removal has been demonstrated.

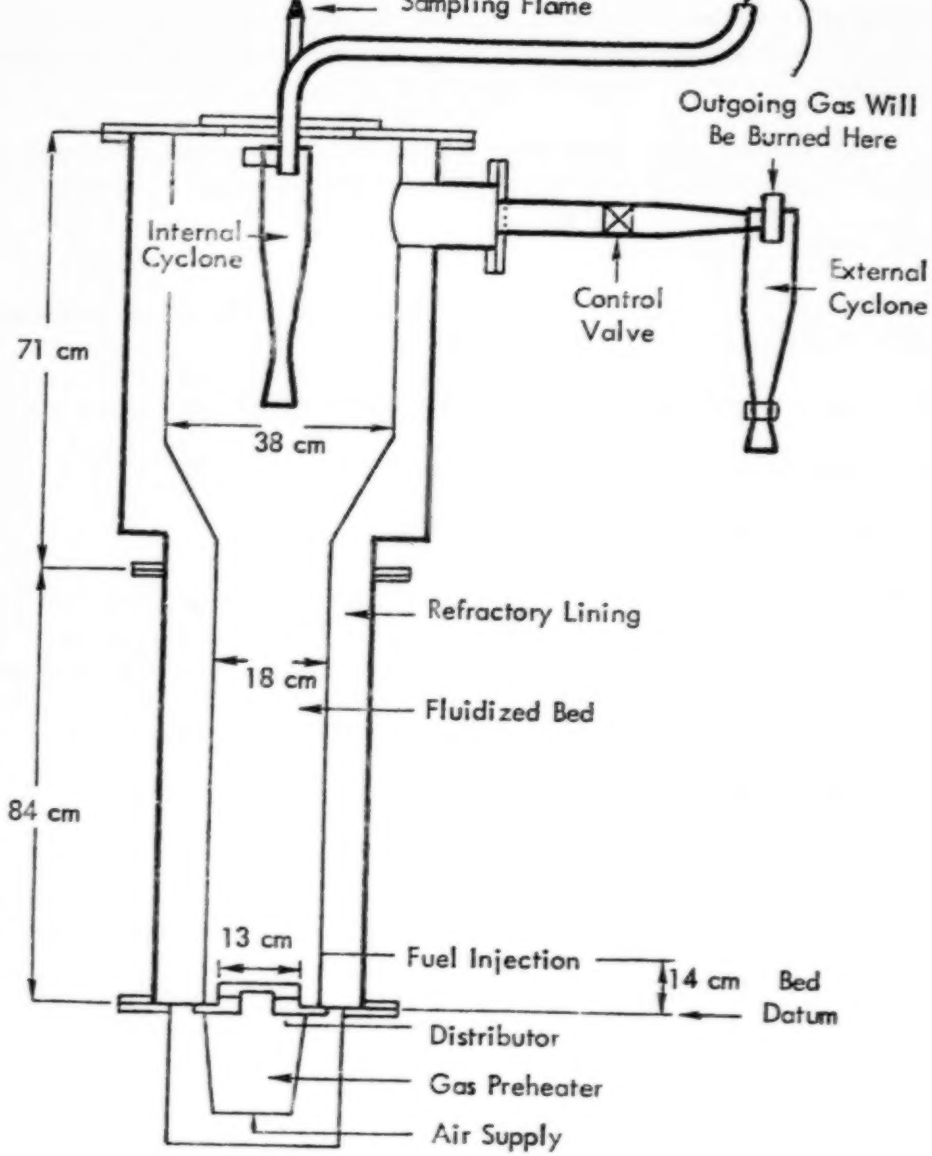
Source: 104.


Air
Air Meter
Propane (for start-up)
Oil
Fuel Metering Pump
Fuel Injector Air
CAFB Batch Reactor
Sample Flame
Sample Gas to Analyzers
Flare

Source: 53.

Figure E-6. Esso, England batch reactor oil gasification system.

The upper section of the reactor was redesigned to permit installation of two internal cyclones and to allow drainage of the cyclone for external sample collection. Internal cooling coils contained in the reactor allowed the temperature to be controlled independently of fuel and air rates. The type of reactor used for these studies is shown in Figure E-7.


Sampling Flame
Outgoing Gas Will Be Burned Here
Internal Cyclone
Control Valve
External Cyclone
71 cm
38 cm
Refractory Lining
18 cm
Fluidized Bed
84 cm
13 cm
Fuel Injection
14 cm
Bed Datum
Distributor
Gas Preheater
Air Supply

Source: 53.

Figure E-7 . Batch reactor.

GLOSSARY AND ABBREVIATIONS

The reader is referred to technical literature for definitions of more specific technical terms. The following glossary defines terms unique to and to clarify procedures used in this study.

Bottom ash residue: The wasted spent bed material from the FBC combustion chamber. Commonly a mixture of limestone or dolomite and coal or oil combustion products.

CFA: English fly ash

Constituent: Signifies any of the several chemical elements or ions analyzed, including chloride, sulfate, iron, lead, nickel, and zinc.

EFA: English fly ash from the Esso Research Centre oil FBC pilot plant in Abingdon, England.

ESBM: English spent bed materials.

FBC: Fluidized-bed combustor.

Fluidized-bed residues: The residue left after the combustion of high sulfur coal or the gasification of high sulfur residual oils in the presence of granular limestone or dolomite. The residues contain unreacted limestone and dolomite, calcium and magnesium sulfur compounds, heavy metals, and coal and oil ash. The residues were flyashes and spent bed materials designated as EFA, ESBM, NFA, NSBM, VFA, and VSBM.

Fly ash residue: Particulate removed from the FBC gas stream.

FSFA: English fine stacks fly ash.

Lysimeter: A porous ceramic-tipped device used to extract, by means of a vacuum, a sample of the column percolating liquid from the strata.

NFA: Refers to New Jersey fly ash from the Exxon coal FBC pilot plant in Linden, New Jersey.

NSBM: New Jersey spent bed material.

Pilot column leaching test: Adding and percolating a known type and quantity of water through residue and subsurface strata materials, in order to collect leachate samples at various points in the column for analysis of constituents.

Pilot-scale test column (pilot test column or test column): A 20.3 cm ID by 3 meter long PVC pipe which contained a simulated natural residue disposal environment.

Potting tests: Plants grown in various sized pots under controlled conditions to investigate the effects of adding FBC residues to soils.

Glossary and Abbreviations (con.)

Residue leaching test: Adding and percolating a known type and quantity of water in order to collect leachate samples for analysis after they have passed through a small 5 cm ID by 30.5 cm high laboratory bench scale column containing a known quantity of fluidized-bed residues.

Simulated environments: Refers to the eight types of prepared layers of stratum materials placed in pilot test columns that represent stratographic sections of different subsurface ground conditions. Included are limestone and dolomite quarries, sanitary landfills, abandoned coal mines, the ocean floor, and clay,sand and silt soils.

Soluble salt extraction test: Often called a "mixing test," it is a batch laboratory procedure wherein the soil or dried plant test sample was mixed with distilled water and agitated for 24 hours. The mixture was then filtered and the liquid passing through the f filter was then analyzed for its constituents.

Total residue digestion test: The dissolving of a soil or plant test sample material by nitric acid, percloric acid, and hydrofluoric acid, and then subsequently analyzing its constituents.

VFA: Virginia fly ash from the Pope,Evans and Robbins coal FBC pilot plant in Alexandria, Virginia

VSBM: Virginia spent bed material.

Water holding capacity: The quantity of water remaining in an initially dried fluidized-bed material after adding water and allowing the water to drain through a filter.